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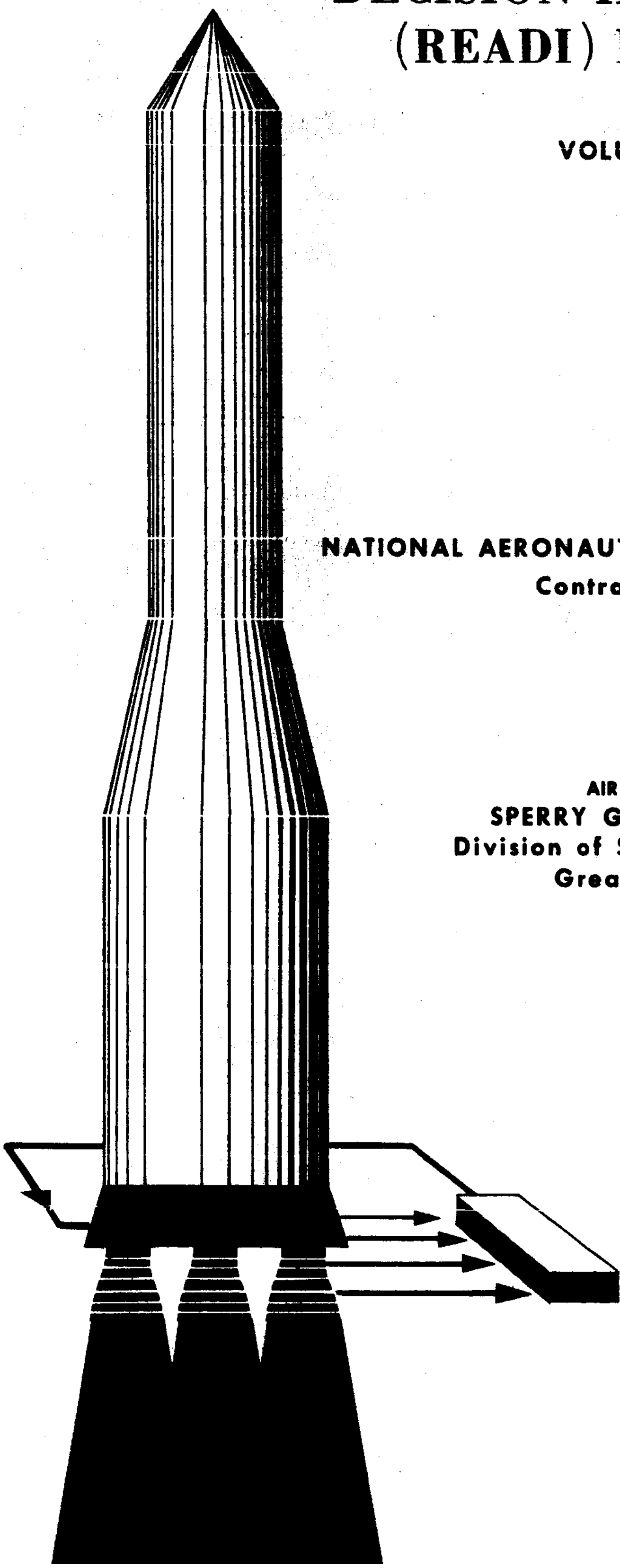
FINAL REPORT
PHASE I

ROCKET ENGINE ANALYZER AND DECISION INSTRUMENTATION (READI) INVESTIGATION

VOLUME I - SUMMARY



Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Contract No. NAS 8-4003

Prepared by

AIR ARMAMENT DIVISION
SPERRY GYROSCOPE COMPANY
Division of Sperry Rand Corporation
Great Neck, New York

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December 1962

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Great Neck, New York

ENGINEERING DEPARTMENT

E.S.Joline

R.L.Smith

J.L.Keller

D.P.Blowney

P.G.Yiotis

J.Harrison

PUBLICATIONS DEPARTMENT

B.R.Maffia

Copy No. ____

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ABSTRACT

The rocket engine analyzer and decision instrumentation concept comprises an on-board electronic system that analyzes the condition of a rocket propulsion system and takes corrective action, either automatically or through the pilot, in order to increase the probability of mission success and safety of the crew.

This concept has been investigated to:

- determine its economic feasibility
- develop a design approach
- gain familiarization with the functional operation and equipment required for a typical system.

A philosophy of approach and detailed design and evaluation procedure are described in which the input data and assumptions are clearly identified and the calculations are performed by a digital computer.

An equipment configuration is described and special reliability techniques are discussed which will permit achieving the functional and reliability requirements as determined by the design procedure.

These design and equipment approaches have been applied to a representative mission-vehicle-engine combination. The results indicate that application of the READI concept to launch vehicles offers a substantial potential return in reduction of mission risk.

FOREWORD

This Final Report on Rocket Engine Analyzer and Decision Instrumentation has been prepared for the National Aeronautics and Space Administration by the Air Armament Division of Sperry Gyroscope Company Division of Sperry Rand Corporation, Great Neck, New York, under Contract No. NAS 8-4003.

The program was initiated by Mr. H. Burlage, Office of Liquid Rockets, NASA Headquarters, Washington, D.C., and has been under the technical cognizance of Messrs. D. Pryor and K. Chandler, P & VE, Marshall Space Flight Center, Huntsville, Ala.

Personnel from Reaction Motors Division of Thiokol Chemical Corp. who contributed to the program include W. Brewington, W. M. Bogert Jr., A. M. Brukardt and E. Tesch.

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Section I
INTRODUCTION

SECTION I

INTRODUCTION

The accomplishment of the United States space program objectives in the next decade will require development of increasingly powerful launch vehicles and propulsion stages. These requirements for greater thrust will be met by development of larger engines and by clustering more engines in a stage.

The size and cost of these engines and vehicles, and difficulties in simulating the space environment may make it economically unfeasible to attain and demonstrate an adequate reliability and confidence factor in advance of the first manned flights.

In order to tolerate attainable reliabilities and the uncertainties in reliability estimates, a concept has been proposed for an instrumentation system that would minimize the consequences of an engine malfunction to the safety of mission and crew. This system concept has been named Rocket Engine Analyzer and Decision Instrumentation (READI).

Although the READI concept appeared attractive intuitively, it was not self evident that when the reliability of the transducers and electronic equipment are considered along with the somewhat limited availability of engine corrective actions, that the addition of a READI system to the vehicle would provide sufficient improvement in mission success probability to justify its cost. NASA therefore recognized the need for a conceptual investigation of the concept. The Sperry Gyroscope Company, having the particular experience and skills needed to achieve an integrated approach, was selected to undertake the study in February 1962.

Sperry obtained the services of Reaction Motors Division of Thiokol Chemical Corporation to perform detailed analyses of rocket engine system and components. In addition, a number of trips were made to Rocketdyne, Pratt and Whitney, Aerojet-General, and Aerospace Corporation. These companies were cooperative in supplying failure data and failure effects analyses on engines and transducers for space application.

This report constitutes the final report of the investigation. It is organized to answer the following questions:

1. How effective would a READI system be in reducing mission risk?
2. How would such a system be designed and evaluated?
3. How would a typical READI system function and what equipment would be required?

Section II

OBJECTIVES AND GENERAL CONCEPT

SECTION II

OBJECTIVES AND GENERAL CONCEPT

The function of READI is to sense abnormal operation of rocket engine propulsion systems and take remedial action. The end objective is to improve the likelihood of accomplishing mission objectives, including the safe return of the crew on manned flights.

For purposes of this study the propulsion system is considered to include the rocket engine itself, and the associated pumps, controls, tankage, tankage pressurization system, and thrust vector actuation means.

READI is primarily an on-board system that will sense signals from the propulsion system directly. However, it will also exchange information with other equipments such as the guidance and control system, fuel energy management system, propellant utilization system, telemetry system, ground checkout system, and any other associated systems. On manned missions some READI decisions based on appropriate READI displays will be made by the crew.

In addition to the remedial action commands that READI supplies to the engine, it may also provide command inputs to the engine for in-flight test, for checkout of parts of a propulsion system prior to use, or for double checking a malfunction indication while the engine is operating. On longer missions for which an in-flight repair capability exists, READI will localize and indicate the repair operation required.

Section III
VALUE OF READI TO MISSION

SECTION III

VALUES OF READI TO MISSION

The value of READI in decreasing the risk of mission and crew loss will be a function of the nature of the particular mission, vehicle stage and engine, and the cost and reliability of the READI equipment components. In order to investigate the feasibility of the READI concept, a set of standard models has been adopted for these systems against which the READI evaluation can be made.

In order to assess the significance of the conclusions reached, it is essential to have an understanding of these assumptions. Each of the models used for the evaluation will, therefore, be described. The conclusions will then be presented, and the sensitivity of these conclusions to variations in the models will be discussed.

3-1. MISSION MODEL

The degree of success or failure of a mission can be judged on whether or not the scientific objectives of the mission have been accomplished, and the safe return of the crew achieved. The value of READI will be in its ability to increase the probability of successfully accomplishing these objectives.

To determine the effect of READI functions and malfunctions on mission objectives, some way must be found for evaluating the effect of a particular action at a particular point in the mission on the ultimate success of the end objectives. To do this, a mathematical model of the mission is required such as the simplified one shown in figure 3-1. Two possible end conditions are assumed for the crew:

- crew safe return
- crew loss.

Two possible end conditions are assumed for the mission:

- successful mission
- aborted mission.

Many possible different paths or chains of events are possible between the start of the mission and arrival at one of the sets of end conditions. At any point on these paths the probability of

accomplishing each of the end objectives can be estimated. If each of the possible end conditions is assigned a weighting factor or loss, an expected loss or risk can be computed by the summation of each possible loss multiplied by its probability of occurrence.

The risk factor used in the design and evaluation studies combines the risk of crew loss with the risk of mission loss using a weighting factor of 10 for the value of the crew. It is to be understood however that each of these reliabilities independently must exceed a minimum acceptable level before use of the combined factor is appropriate.

To arrive at the mission stage model, all propulsion system failures are classified into five categories in accordance with their mission effects.

1. Normal (N) - within expected performance limits
2. Degraded (D) - marginal performance can be compensated for by subsequent stages or may allow accomplishing secondary objectives.
3. Failed (F) - more severe performance degradation not fully compensatable in subsequent stages but may allow alternate missions. Immediate abort not required for safety but may be best mission decision.
4. Abort (A) - serious malfunction for which there is an immediate threat of vehicle destruction.
5. Catastrophic Destruction (X) - malfunction resulting in loss of crew and vehicle.

It is assumed that the vehicle stage carries one percent extra fuel. This excess can be used to correct for small malfunctions and still achieve the normal status. The degraded classification is used for velocity errors between 0 to 135 ft/sec, or excess burning time greater than 10 percent.

The mission states at the end of stage 2 that would result, assuming these failures, are shown as nodes at the right of figure 3-2. To compute the effective risk at each node, it is necessary to assume transitional probabilities for the subsequent stages of the mission as shown on figure 3-3. The figures used for studying stage 2 assume that a READI system is used in stages 1 and 3. A computer program has been prepared that will compute the risks at each state node for a mission divided into any number of stages and any number of stage states, given the transitional probability matrix for subsequent stages and the end loss weighting factors.

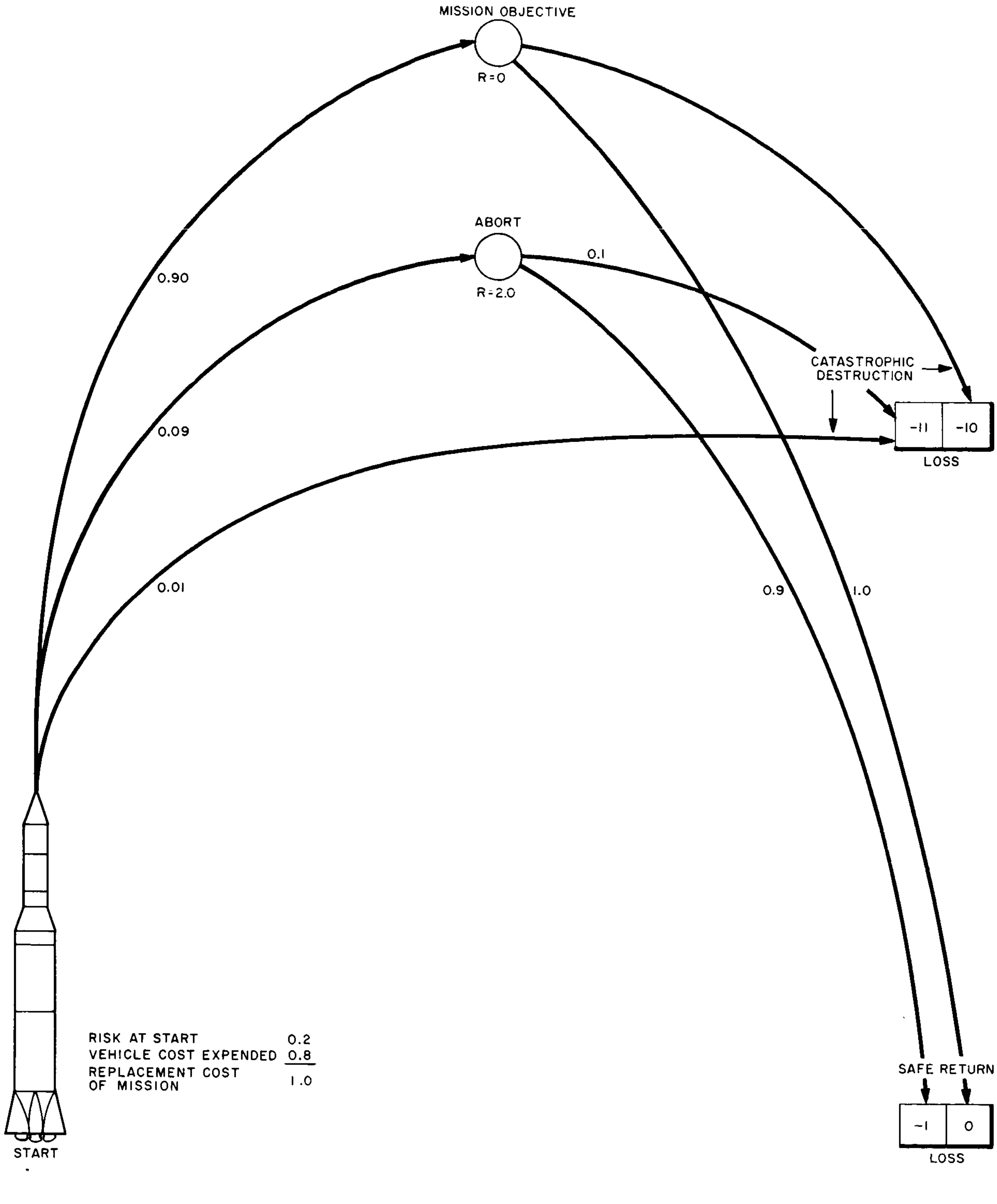


FIGURE 3-1

SIMPLIFIED MISSION MODEL
(NO READI)

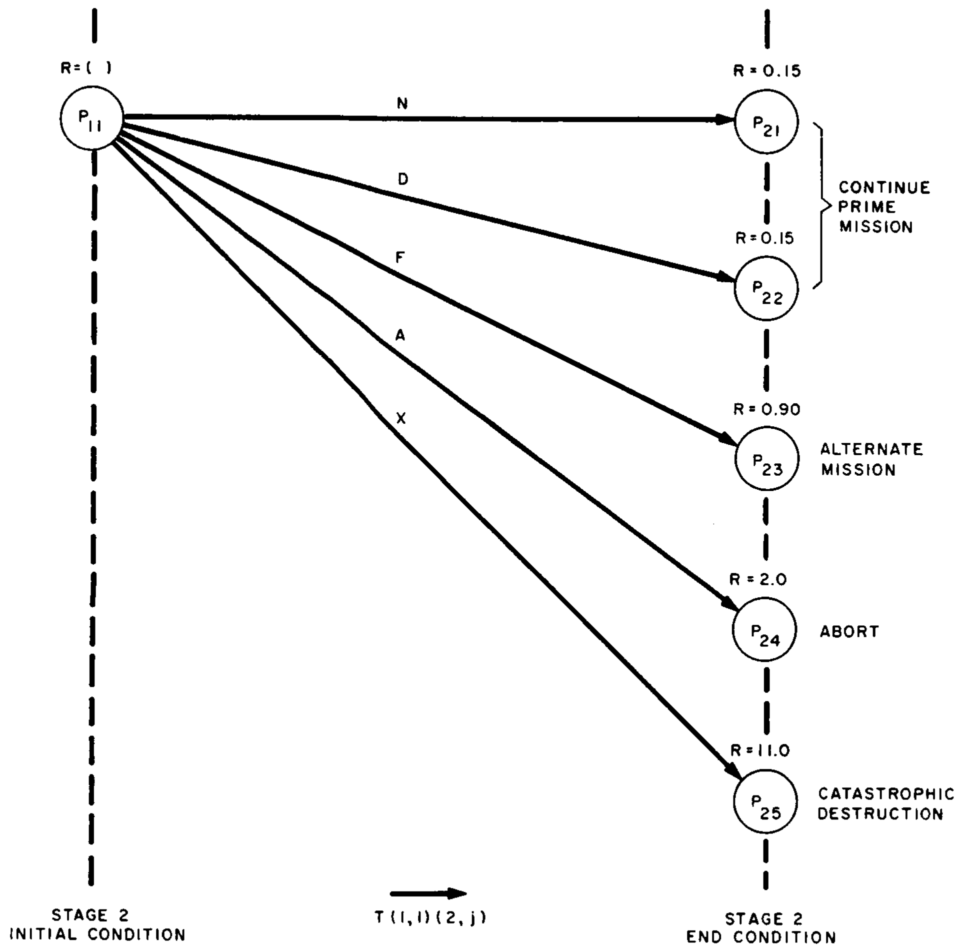
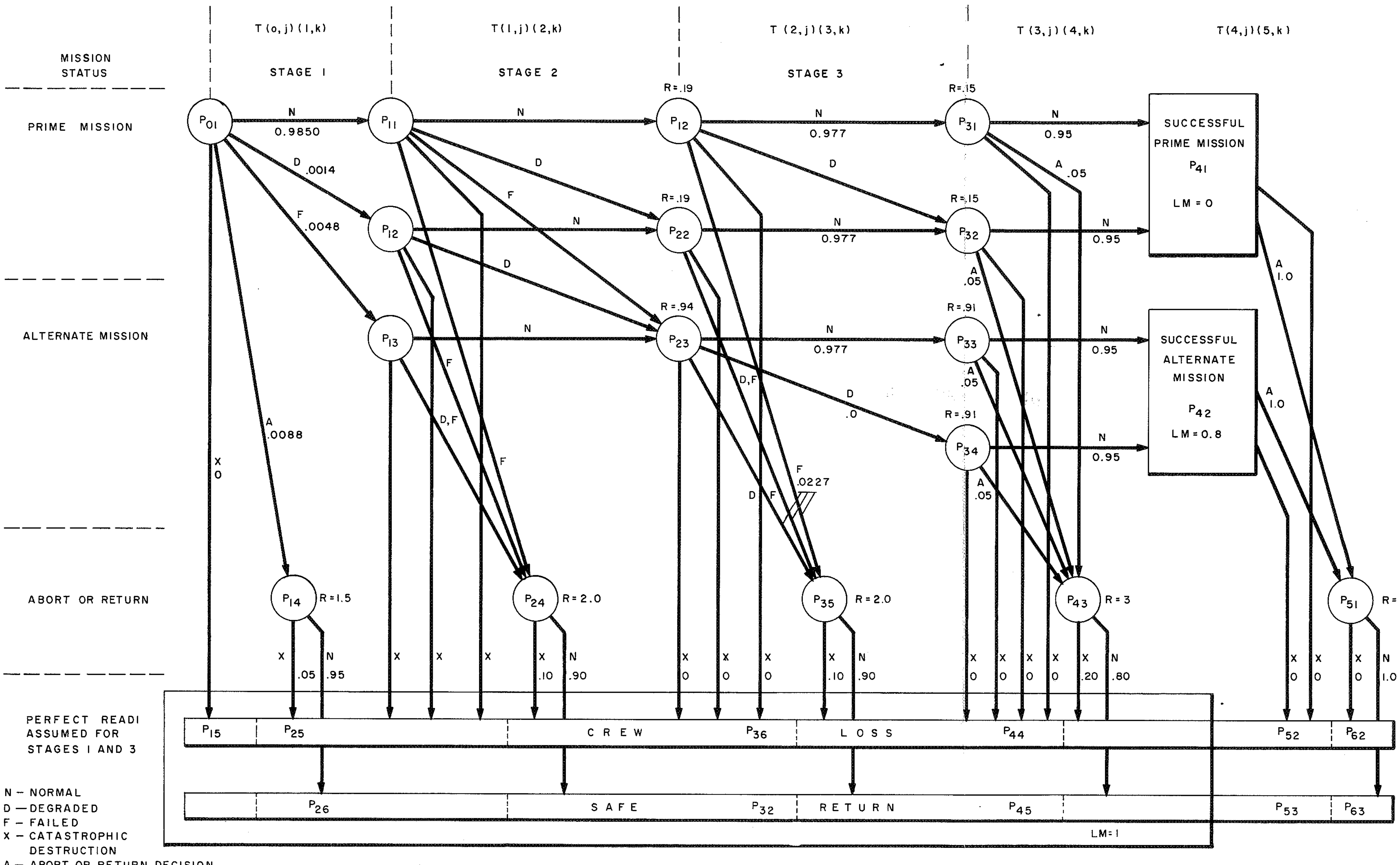


FIGURE 3-2
MISSION STAGE MODEL



$$P(i,j) = \sum_k P(i-1,k)\ T\{(i-1,k)(i,j)\}$$

$$R(i,j) = \sum_k R(i+1,k)\ T\{(i,j)(i+1,k)\}$$

FIGURE 3-3
MISSION MODEL

The transitional probabilities shown in parenthesis on figure 3-2 are for a typical READI, while those not in parenthesis are for no-READI. The value of READI is in reducing the probability of going to a high risk state and increasing the probability of a low risk state.

3-2. VEHICLE MODEL

The organization and scaling of READI's data processing and computing capabilities is a function of the vehicles staging and the number of engine clustered per stage. The three stage vehicle model assumed is shown in figure 3-4. The first and second stages each employ clusters of five engines, while the third stage has only one engine.

Since any weight added by READI would reduce the payload lifting capability, a weight penalty is charged against the equipment according to its location in stages of the vehicle.

3-3. MODEL ENGINE

The ability of READI to affect the transitional probabilities between states is a strong function of the availability of remedial actions that can be taken should a malfunction occur.

The available alternate actions assumed for the model second stage engine, shown in figure 3-5, are as follows:

1. shutdown
2. fast shutdown
3. restart
4. engine out capability either by sacrifice of portion of payload or by engine overrating capability during emergencies.

Shutdown and restart are already available in current state-of-the-art second stage engines. Fast shutdown for emergencies could be added by minor modification to the valving. Fast shutdown is not normally used because of possible damage to the engine but is acceptable for emergencies. Thrust overrating is believed possible with current engines but would require some modifications and an engine test program to prove-out. The increased thrust would be accomplished by trading off reliability so it would be feasible only as an emergency action.

The assumed failure characteristics of the engine are equivalent to a relatively mature engine with a total failure rate of about

0.01 per mission. With no remedial action this rate would be prorated among the four failure categories as follows:

	Rate
failure to start	10×10^{-4}
premature safe shutdown	20×10^{-4}
explosion	40×10^{-4}
severe off-design operation	30×10^{-4}
Total	100×10^{-4}

3-4. MODEL READI

A well-designed, comprehensive but not necessarily optimum READI system having the configuration shown in figure 3-6 has been assumed for the evaluation. The reliability figures used for the transducers are based on experimental data taken from actual rocket testing and are considered to have conservatively high failure rates. The average order of magnitude for missed alarm type failures is 10×10^{-4} per mission. The raw transducer false alarm rate is also considered to be 10×10^{-4}. However, this is reduced by an order of magnitude by the computer's checking methods and information redundancy.

3-5. READI COST MODEL

The reduction in mission and crew risk that is expected through application of READI is partially offset by the cost of adding the READI system to the vehicle. The term cost as used here is all inclusive and is intended to include indirect as well as direct costs.

A cost model has been assumed for making optimization trade-offs, and is illustrated in figure 3-7. For the model mission, assuming a rather complete READI system, the total cost of one million dollars per vehicle is assumed. This includes a $300,000 component of development and test costs that has been shared over 20 vehicles. In system optimization studies it has been assumed that half the total cost is fixed for a particular vehicle installation, while the other half varies directly with the number of transducers used on the engine. The average cost of adding a transducer, including all variable costs directly attributable to the transducer, is $2,000. For a particular engine optimization study, however, the cost used for a particular transducer will vary widely depending on the nature of the transducer and the complexities of installing it on the propulsion system.

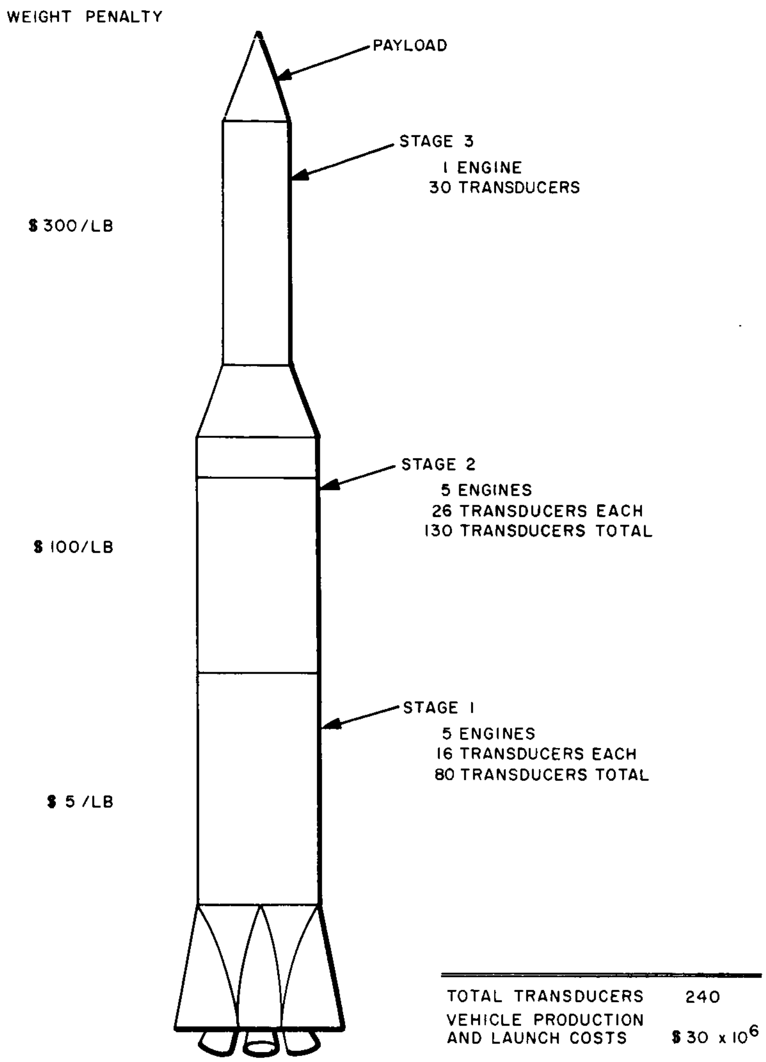


FIGURE 3-4
VEHICLE MODEL

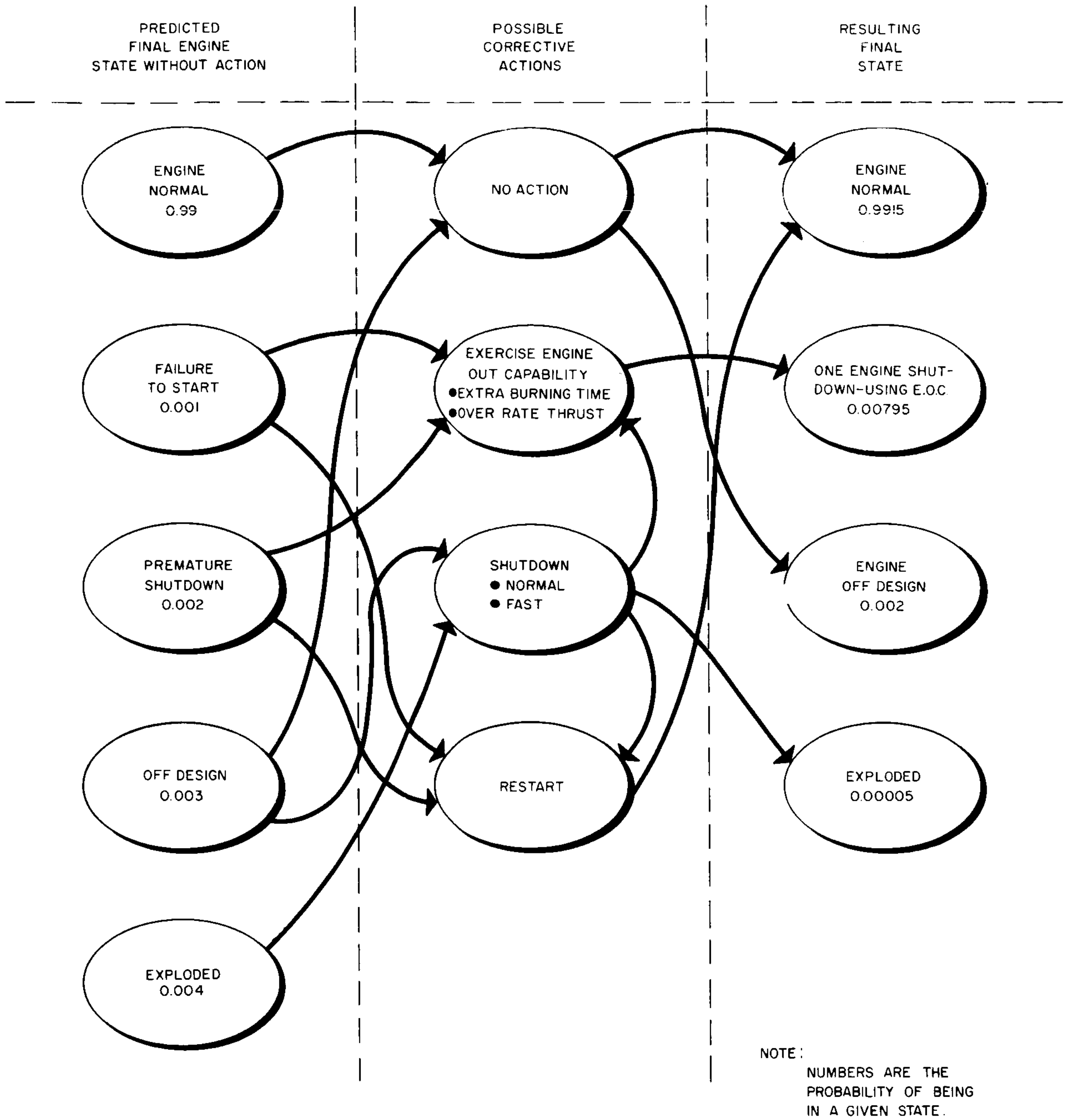
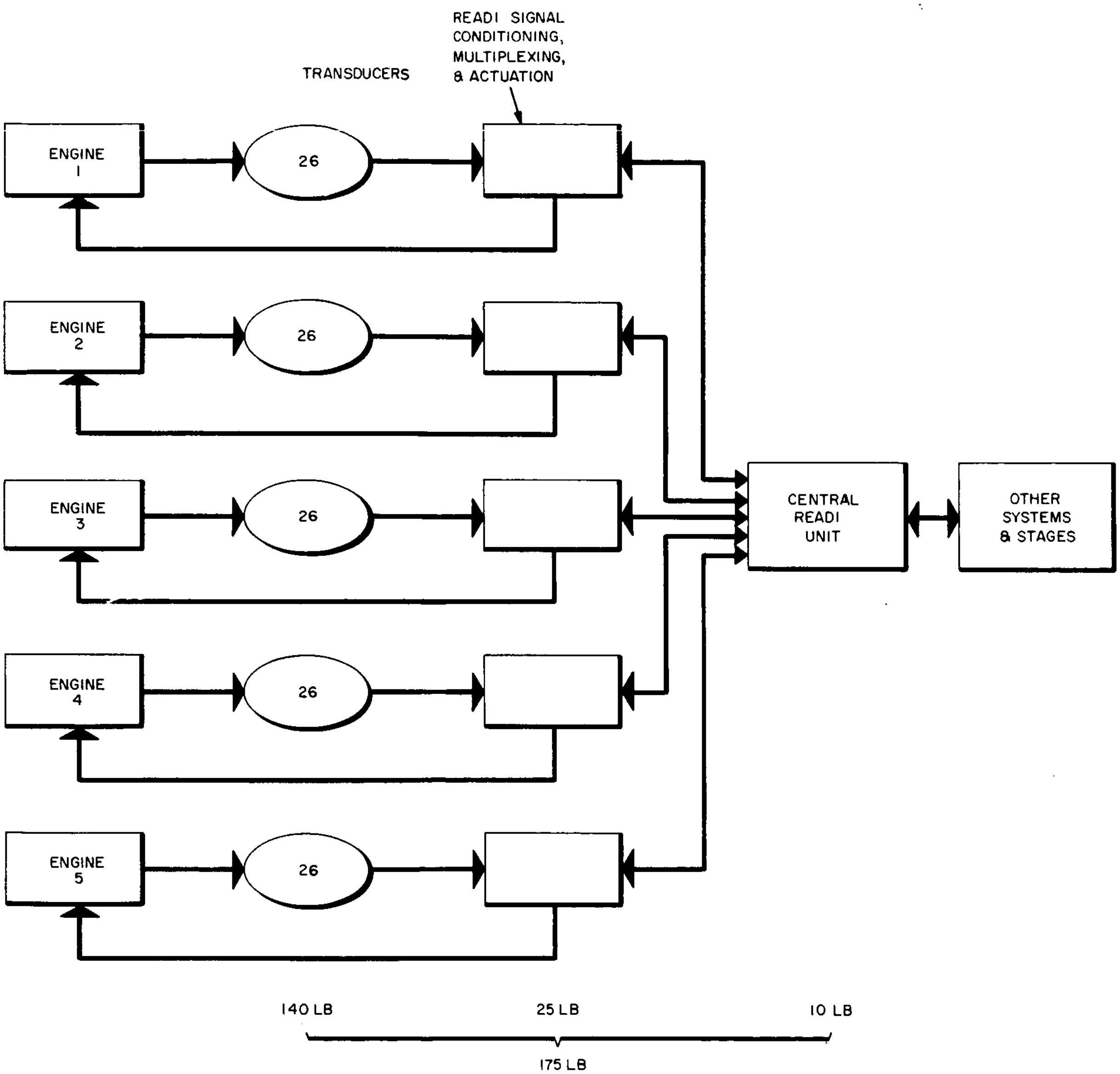


FIGURE 3-5
ENGINE MODEL



AVERAGE TRANSDUCER RELIABILITY ASSUMED (WITHOUT REDUNDANCY, SELF CHECK, ETC.) MISSED ALARM TYPE FAILURE RATE 10×10^{-4} PER MISSION. FALSE ALARM TYPE FAILURE RATE 10×10^{-4} PER MISSION

FIGURE 3-6
READI MODEL - (STAGE 2)

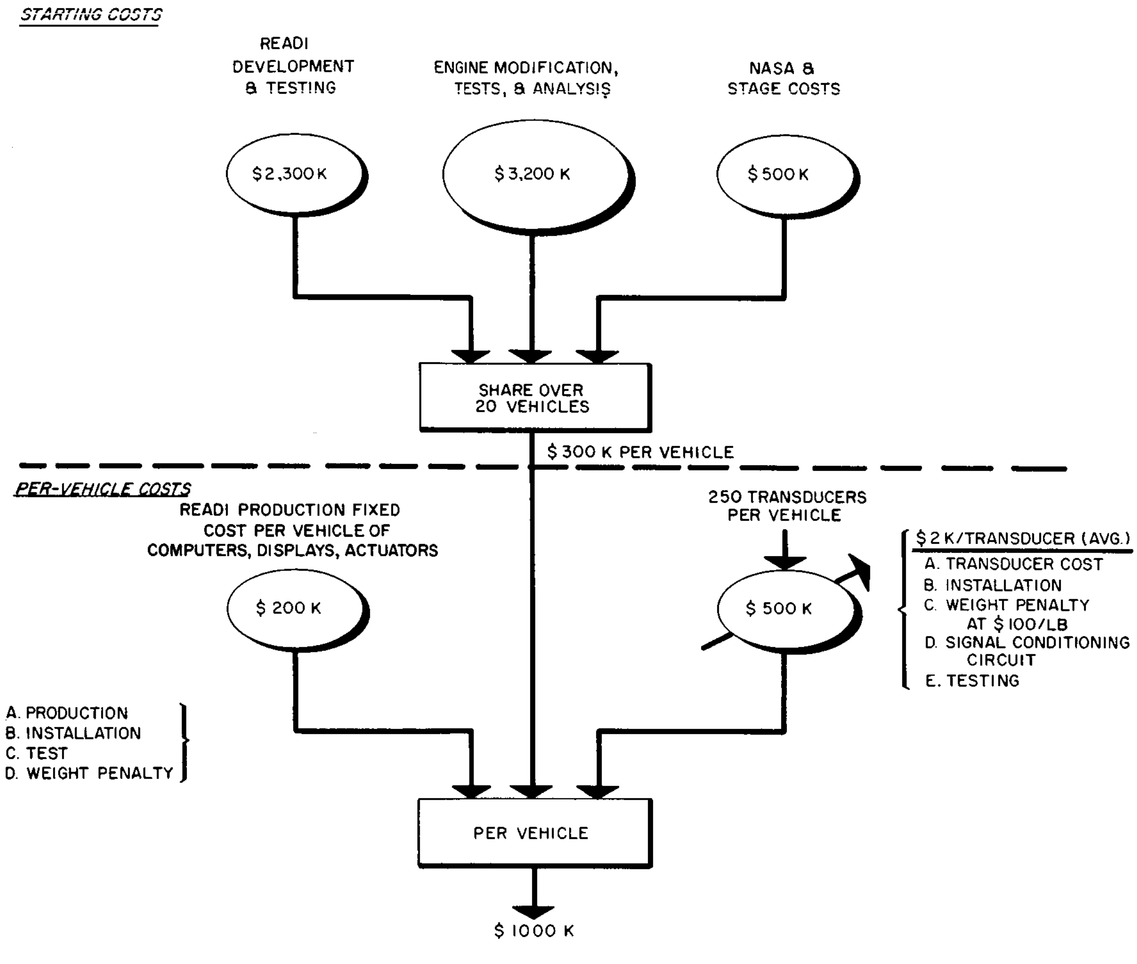


FIGURE 3-7
READI COST MODEL

The cost model therefore includes substantial indirect costs attributable to the READI system and non-recurring developmental cost. Even so, it will be seen that the return in reduced mission risk may far exceed these costs.

3-6. VALUE OF READI

Using the mission, vehicle, engine, and READI cost models just described, the risk factors for a set of trial systems were calculated on a digital computer in accordance with the procedures to be described in the next section.

The trial systems evaluated ranged from systems having a minimum number of transducers to relatively comprehensive systems. Redundancy and other special techniques such as self-check were not employed to improve reliability, and hence the systems do not represent optimum designs.

The risk factor shown for each system in figure 3-8 is in units of mission replacement value. For a typical vehicle second stage, the risk factor would be 0.23 without READI and would be reduced to 0.0136 with a perfect READI that monitored all malfunction areas and always took the best corrective action.

The cost of the trial systems vary from slightly more than the fixed system cost of $200,000 for the simplest system to over twice this amount for the most complicated system.

The best of the trial systems is found by drawing a risk versus cost trade-off line with a slope of -1, and moving it upward until it intersects a system point. (For the particular set of models used, a risk factor of unity is approximately equal to 50 million dollars). The system intersected by the lowest position of the line (#16) is the best system, since the incremented cost of obtaining additional risk reduction would exceed the increment of risk reduction obtained. The resulting risk is 23 percent of the risk with no READI.

These results, shown in terms of the overall mission in figure 3-9, indicate that the addition of a READI system to the second stage of the model vehicle can reduce the average cost of the space operation by 16 percent with only a 1 percent investment in equipment.

3-7. SENSITIVITY OF RESULTS TO VARIATIONS OF THE MODEL

The results of the application of READI to the assumed mission, vehicle, and engine model show that READI can have a very

substantial potential value; however, these results cannot be generalized to apply to all actual launch vehicles since the nature of the equipment and mission may differ substantially from the model assumed here. Some indication of the trends that can be expected for differing sets of circumstances can be obtained by perturbing the parameters of the model.

Figures 3-10, 3-11, and 3-12 show the effects of varying three of these parameters:

- availability of engine remedial actions
- transducer failure rates
- crew mission value ratio.

The height of the bars in figure 3-10 indicate the risk factor obtainable with a perfect READI for engines having various combinations of available remedial actions. Engine H, the one assumed for the model, has the complete complement of remedial actions: shutdown, fast shut-down, restart, and engine out capability, as a result this engine achieves the greatest risk reduction. However, Engine A is capable of achieving a large part of this risk reduction through the use of shutdown action alone. Therefore, it can be seen that although the value of READI is augmented by engine flexibility, substantial returns can be obtained even with the simplest engines.

Figure 3-11 shows the risk factor for a typical READI system using one-fifth and five times the estimated transducer failure rates listed in Appendix E. The total risk factor is broken down into four components:

- the residual risk for a perfect system due to incomplete compensation by the remedial actions
- risk due to incomplete monitoring by the typical system
- false alarms
- missed alarms.

The risk due to false alarms can be reduced substantially from the levels shown by application of the reliability techniques proposed. The bar for the high $5\lambda_t$ failure rate shows that if these techniques are not used and unreliable transducers are employed, the risk with READI can easily exceed the risk without READI.

Some idea of the effect of the assumed crew/mission value ratio on the feasibility of READI is given by figure 3-12. A crew value

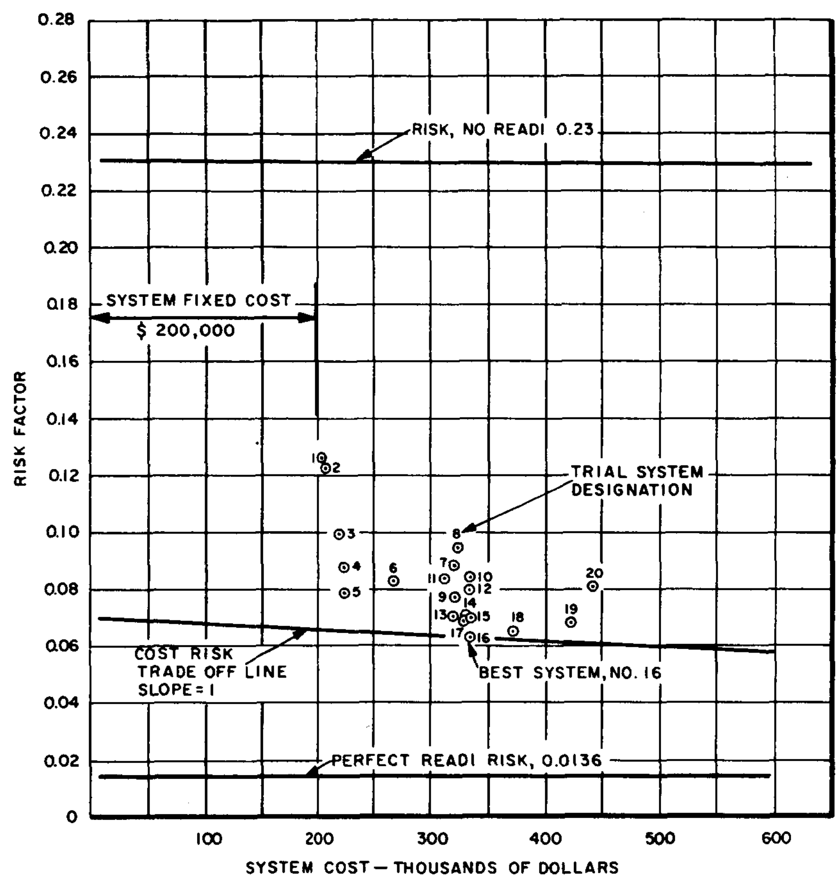


FIGURE 3-8 EVALUATION OF TRIAL SYSTEMS EFFECTIVENESS VS COST FOR SECOND STAGE

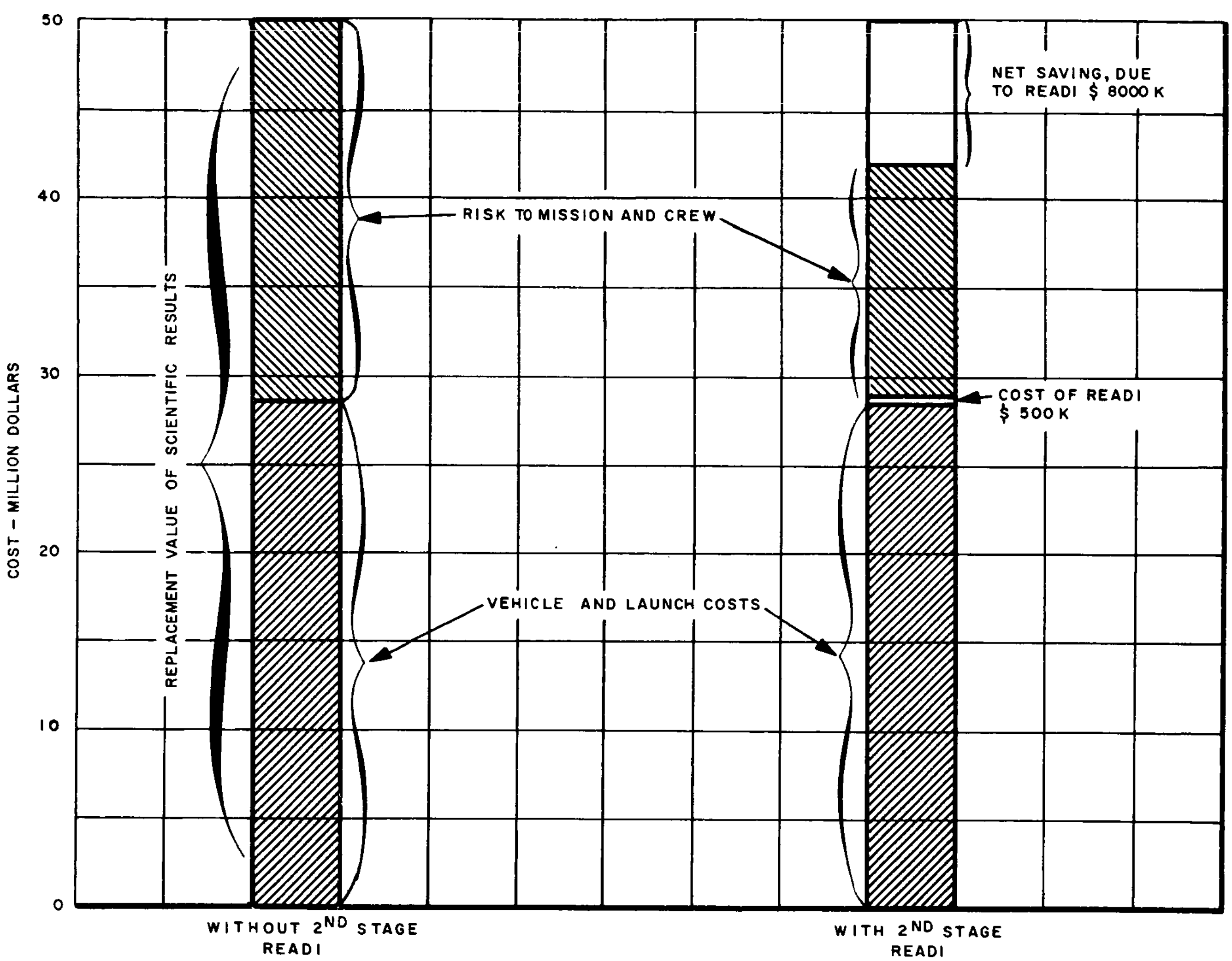


FIGURE 3-9. ECONOMIC FEASIBILITY OF TYPICAL READI FOR VEHICLE SECOND STAGE

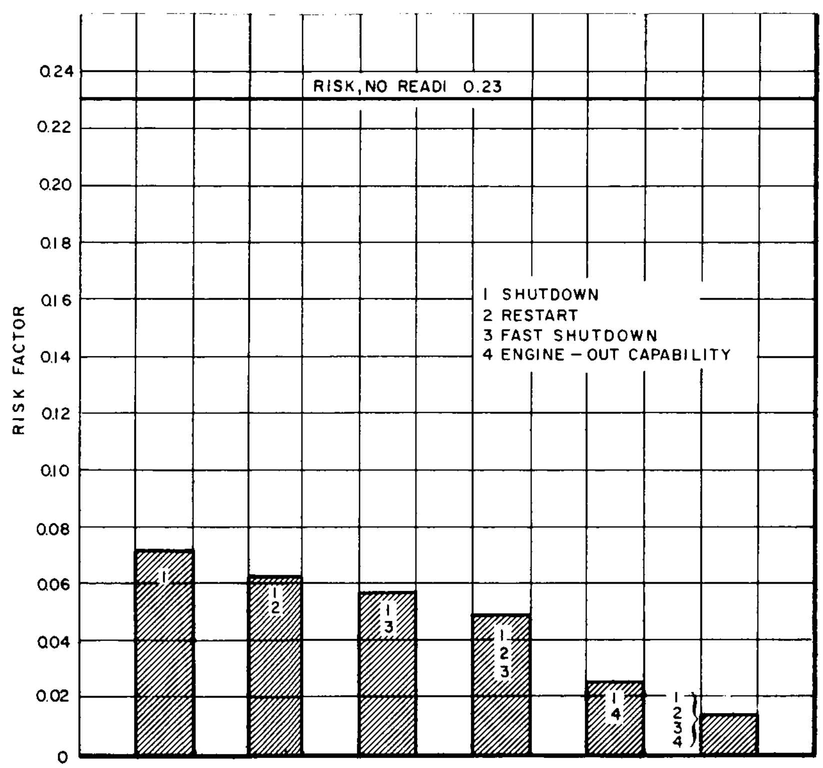


FIGURE 3-10 SENSITIVITY OF RISK FACTOR TO AVAILABILITY OF ENGINE REMEDIAL ACTIONS (PERFECT READI – SECOND STAGE)

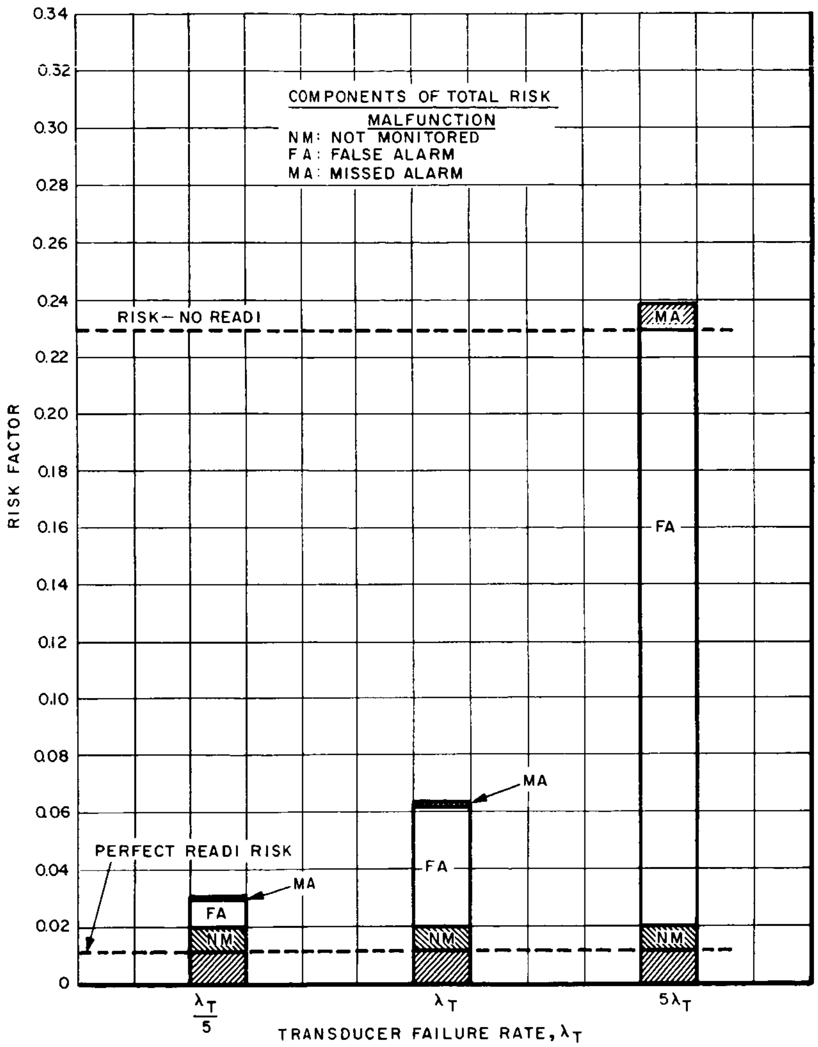


FIGURE 3-11. SENSITIVITY OF RISK FACTOR TO TRANSDUCER FAILURE RATE, λ_T
(TYPICAL READI FOR SECOND STAGE)

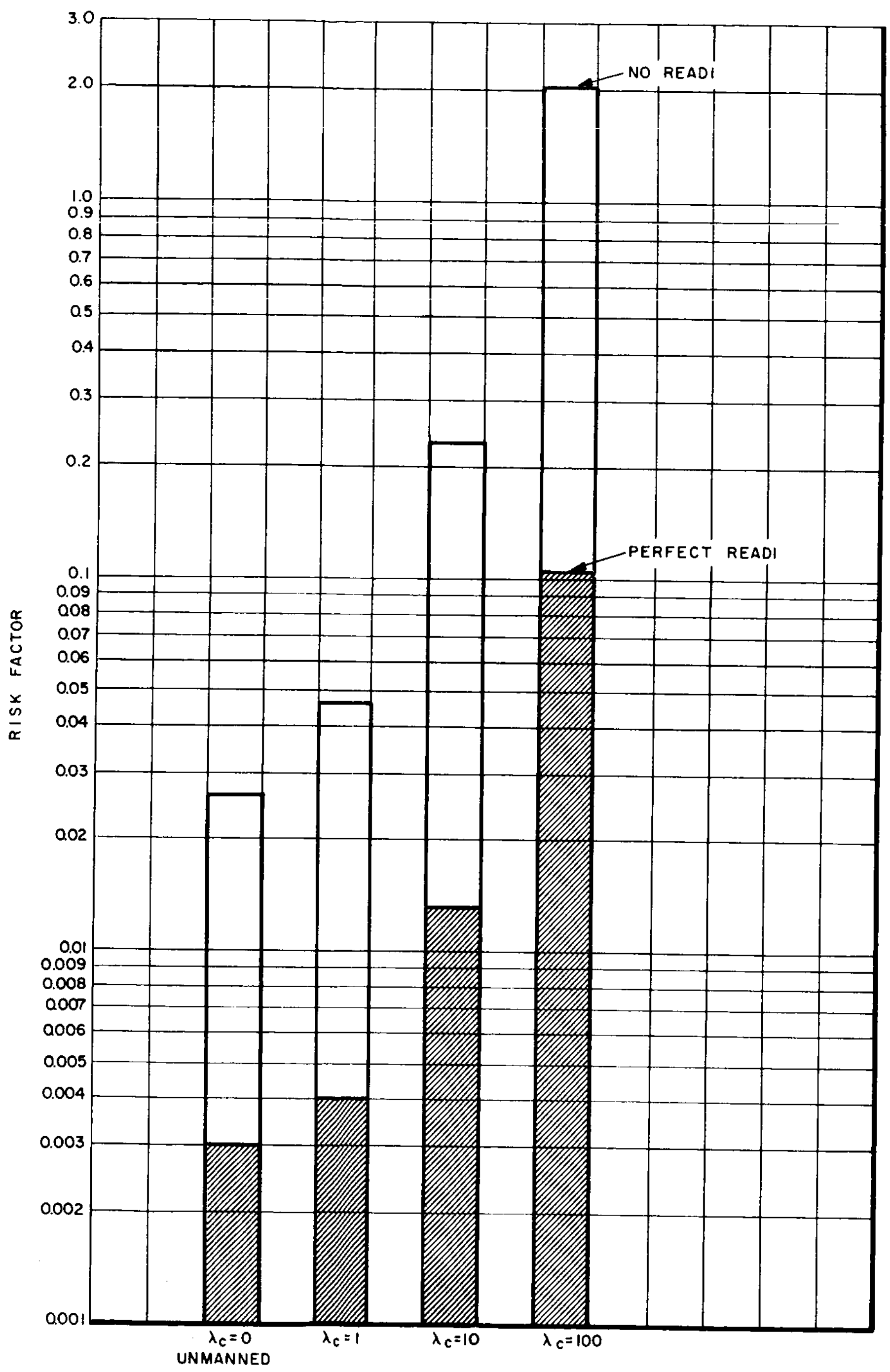


FIGURE 3-12 SENSITIVITY OF RISK FACTOR TO CREW / MISSION VALUE RATIO, λ_c
(PERFECT READI FOR SECOND STAGE)

of zero corresponds to an unmanned mission. A crew value exceeding 1, the mission replacement value, implies a willingness to sacrifice the mission to save the crew. Comparison of crew safety and mission reliability design objectives being used for actual manned missions would indicate that a weighting value of 100 is appropriate. Using this value, however, the model mission would not be feasible without READI since the risk factor for the second stage alone would exceed unity which implies that the risk at the start exceeds the value of the possible mission gains. The compromise value for λ_c of 10 was used in the actual evaluation model. For $\lambda_c = 1$ and $\lambda_c = 0$ the value of READI is naturally less since the capability of preventing catastrophic destruction is weighted less heavily. However, even for these cases the cost of the equipment is easily justified by risk reductions and the resultant decrease in the average cost of accomplishing the mission.

From a study of these results it can be concluded that a READI system would significantly improve the reliability of present and future launch operations.

Section IV

DESIGN AND EVALUATION OF A READI SYSTEM

SECTION IV

DESIGN AND EVALUATION OF A READI SYSTEM

It became apparent early in the READI program that the design and evaluation of a READI system for a particular mission vehicle and engine was a very complicated procedure that would be extremely difficult to handle on an intuitive basis. Perhaps the chief reason for this complexity is that malfunctions arise from many different sources, each having a very low probability of occurrence, yet the total adds up to a significant figure. (Individual components contributing a large percentage of the failure rate would probably be fixed by design changes.)

Another reason is that the engine has five phases of operations: prestart, start, run, shutdown and restart. The nature of the engine operation and the types and likelihood of malfunction during each of these phases is completely different, yet one set of READI equipment must serve all five phases.

An appreciation for some of the difficulties that these complexities introduce can be gained by looking at some of the questions that must be answered during the design procedures, such as the following:

1. What malfunctions should be monitored? It is not necessarily desirable to monitor all malfunctions since there may be no remedial action available, or the risk of false alarm, or equipment cost, may outweigh the expected benefits.
2. Which malfunction indication should be selected? Often the same malfunction can be sensed via a number of different parameters and transducers.
3. When does redundancy pay off? Information and transducer redundancy may be desirable under some conditions.
4. Which should be favored - false or missed alarms? Transducers can often be selected and arranged to favor either false or missed alarms at the expense of the other.

Although it is intuitively evident that the answers to the above questions depend in some way on input data, such as engine and transducer failure rates, tolerance of the mission to velocity errors, and many others, the exact effects of these inputs on system tradeoffs are not easy to assess. An organized approach was therefore devised that would:

- Identify the input data required and show its relationship to system performance
- Clearly define the steps in the design procedure
- Make maximum use of machine computation techniques so that new systems and data refinement can be readily handled.

4-1. READI SYSTEM ANALYTICAL MODEL

The analysis of READI system operation in combination with a propulsion system is facilitated by use of an analytic model that subdivides the overall operation into simpler parts. The model shown in figure 4-1 has been found to be useful for this purpose.

Random malfunctions of the propulsion system are considered to be the inputs to this model. These malfunctions affect measurable variables of the propulsion system, S_q. These measured variables are then sensed by a set of transducers, and the resulting information is processed to form decisions as to the remedial action to be taken. This action may be taken automatically, or the pilot may institute it as a result of display indications.

A. PROPULSION SYSTEM STATE SPACE

The condition of the propulsion system at any instant of time can be thought of as a point in an n dimensional state space, where the values of n parameters are sufficient to define the possible operating conditions. Since operating conditions resulting from many different types of malfunctions are included in this space, many dimensions are required to describe all the possibilities.

Possible system states, resulting from a malfunction and the malfunction effects, will comprise a region in this space.

1. Propulsion System Malfunctions

Malfunctions in the propulsion system equipment are defined as random, statistically independent failures. These include

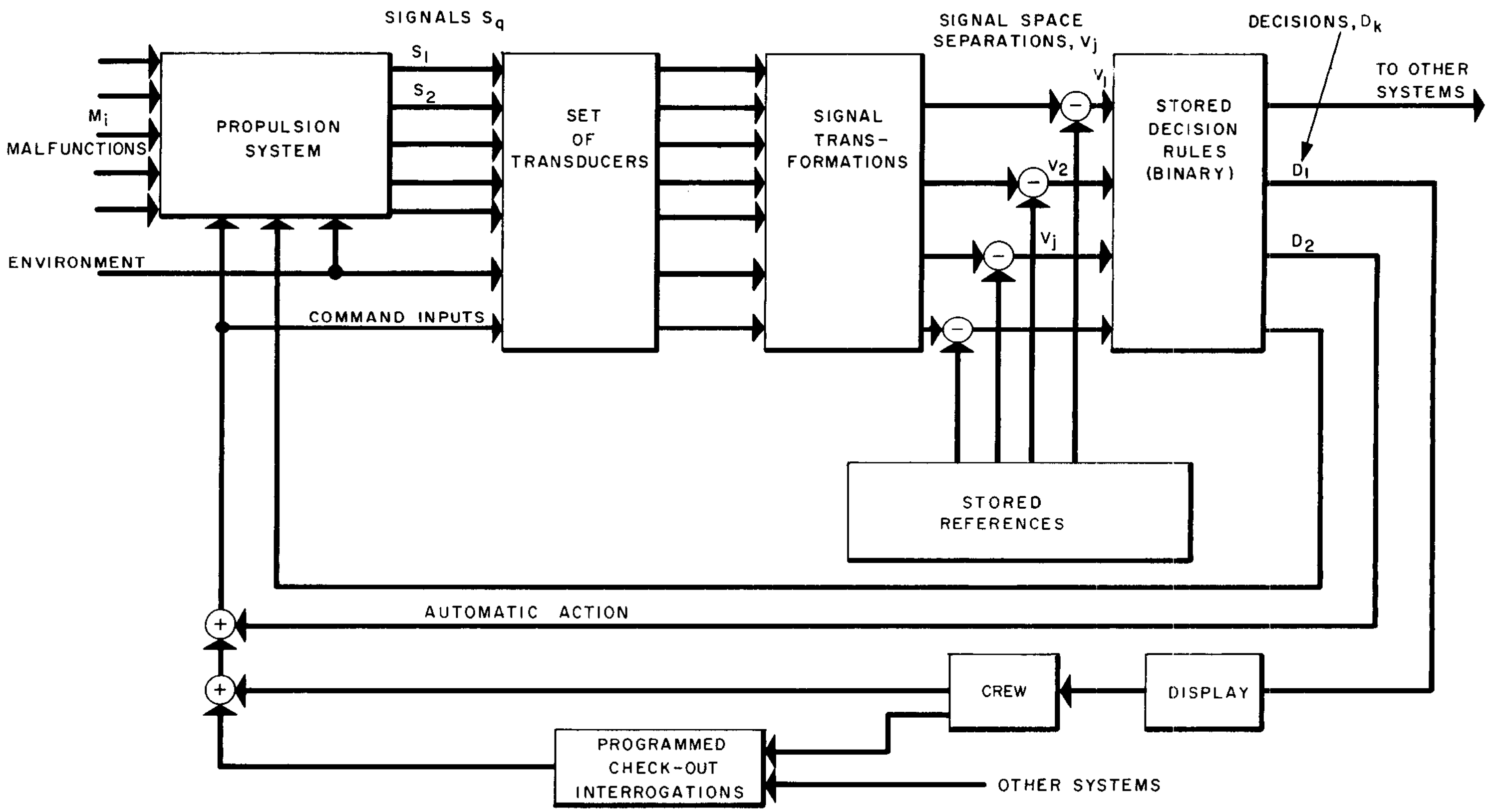


FIGURE 4-1
SYSTEM ANALYTICAL MODEL

stuck valves, leaks, and shorted wires. Groups of similar malfunctions that can be treated the same in all respects can be lumped together and given a common name.

Some propulsion system failures, such as leaks, will not be discrete events, but will have a continuous range of amplitudes or degrees of degradation. Since a mission loss will result from relatively large degradations only, the amplitudes above a certain value are considered as malfunctions.

When the effects of a malfunction and the consequent sensed indications depend significantly on chance, the malfunction is subdivided into a set of separate malfunctions each having an indication not dependent on chance. The total malfunction probability is then prorated among the new set in accordance with the likelihood of each of the end indications.

Malfunctions are identified by the symbol m_i, where the subscript i identified the particular malfunction. Also, each malfunction will have associated with it a probability of occurrence, $P(m_i)$.

2. Sensed Signals

When a malfunction occurs, it will start a cause and effect chain of events to occur in the propulsion system resulting in changes in a number of measurable variables. The set of sensed signals considered for use by the READI system is identified by the symbol S_q.

3. Signal Space Separations

A q dimensional signal space can be conceived in which each operating condition of the propulsion system or point of engine state space can be located in accordance with its effect on each of the q measured signals available to the READI system. A two dimensional illustration is shown in figure 4-2. By combining and processing sets of these signals, signal space can be separated into regions containing one or more of the smaller malfunction regions. These separations are designated by the symbol V_j which can take on the value 0 or 1, where the value 1 designates the region containing the desired set of malfunctions and 0 designates the remaining region containing normal operation and all other malfunctions.

Signal space separations will be individually synthesized using the available signals after careful analytical and experimental

study of the engine. Some of these V_j regions will respond to the end effects of many different initial malfunctions. Other V_j's will localize the failure to a higher degree by sensing signals from individual components such as values where the malfunctions originate.

By choosing signals that are orthogonal to the desired plane of separation, the signal processing is considerably simplified, and the comparison of a single transducer output to a fixed limit will often suffice.

Separation of signal space for a time varying signal such as a starting transient usually requires a more complicated analysis. One method is to examine sets of experimental or analytically derived transients belonging to the groups requiring separation, and determine the least number of measurements that must be made to separate the groups effectively. The ultimate transformation process may include use of analog models, digital models, filters, non-linear function generators, etc., to transform a measured variable so that it is orthogonal to the plane of separation. These transformed variables are then compared with stored reference variables and a binary indication of the signal space region is generated. Figure 4-3 shows several examples of typical signal space separations.

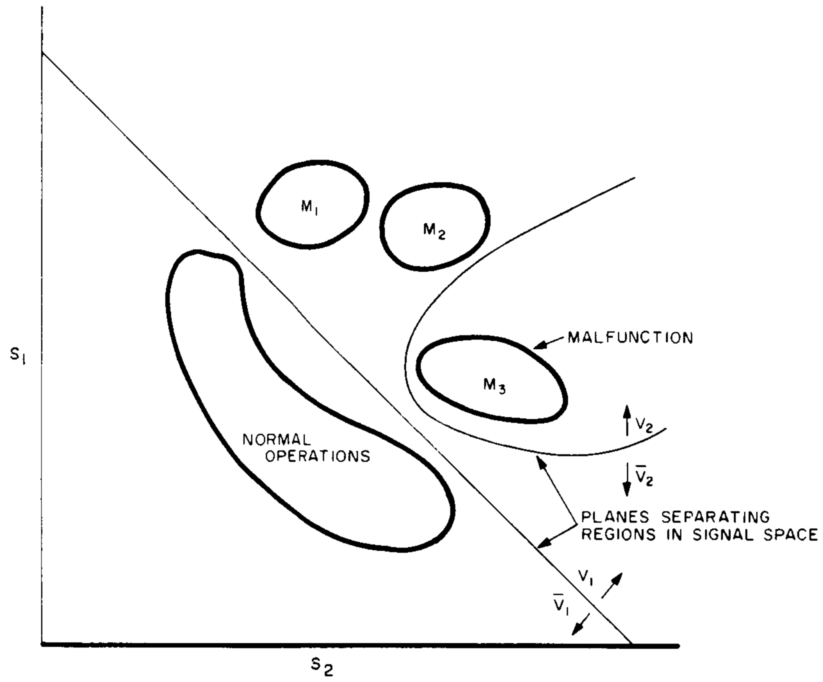
B. DECISIONS

For a particular engine configuration there will be a number of alternate remedial actions available to the READI system. A decision is the selection of a single action or a sequence of actions based on the indicated condition of the engine. The conditions required for a particular decision, d_k, can be expressed as a Boolean equation using the signal space separations, V_j. These equations are called decision rules and are denoted by

$$d_k = \delta_k(V_1, V_2, \ldots V_n)$$

The decision called for by the equation for a particular set of V's is the decision representing the least risk of the available decisions in the loss matrix.

Figure 4-4 illustrates the relationship between malfunctions, signal space separations, and decisions. The failure effects tree shows that V_5 is sensitive to three malfunctions: m_2, m_3, and m_4, while V_1 is only sensitive to one. The logic diagram and logic equations illustrate the Boolean relationship between the V's and the desired decisions.



LEGEND

$\bar{V}_1$ REGION FOR NORMAL OPERATION

V_1 REGION CONTAINING ALL MALFUNCTIONS

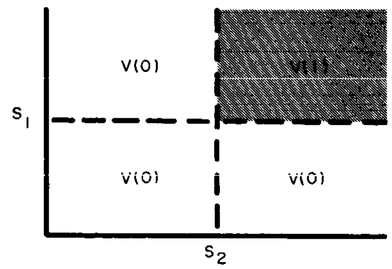
V_2 REGION CONTAINING M_3

$V_1 \bar{V}_2$ REGION CONTAINING M_1 AND M_2

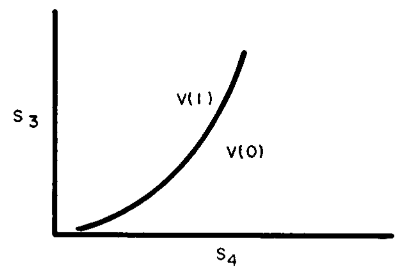
FIGURE 4-2

SIGNAL SPACE DESCRIBING PROPULSION SYSTEM STATES FOR NORMAL AND MALFUNCTION OPERATING CONDITIONS

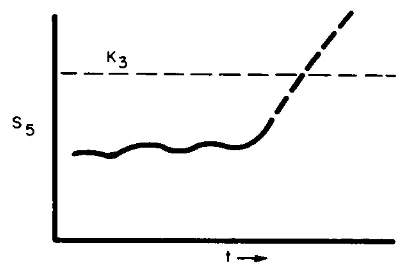
1. BOOLEAN FUNCTION OF n VARIABLES
   $V = S_1 S_2$



2. ARITHMETIC FUNCTION OF n VARIABLES
   $V = 1$ FOR $S_3 > K_1 (S_4)^2$



3. TIME FUNCTION OF n VARIABLES
   $V = 1$ FOR $S_5 + K_2 \frac{dS_5}{dt} > K_3$ OR
   $V = 1$ FOR $\int_0^t S_6 \, dt > K_4$



4. NUMBER OF EVENTS
   $V = 1$ FOR $\Sigma \, (S_7 > K_5) > K_6$

   CODE
   V = SIGNAL SPACE SEPARATION
   S = SIGNAL
   K = CONSTANT

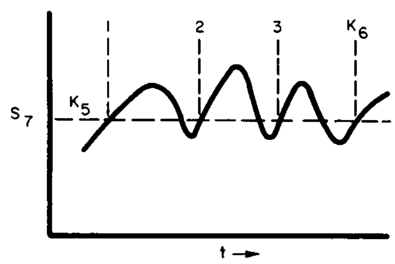
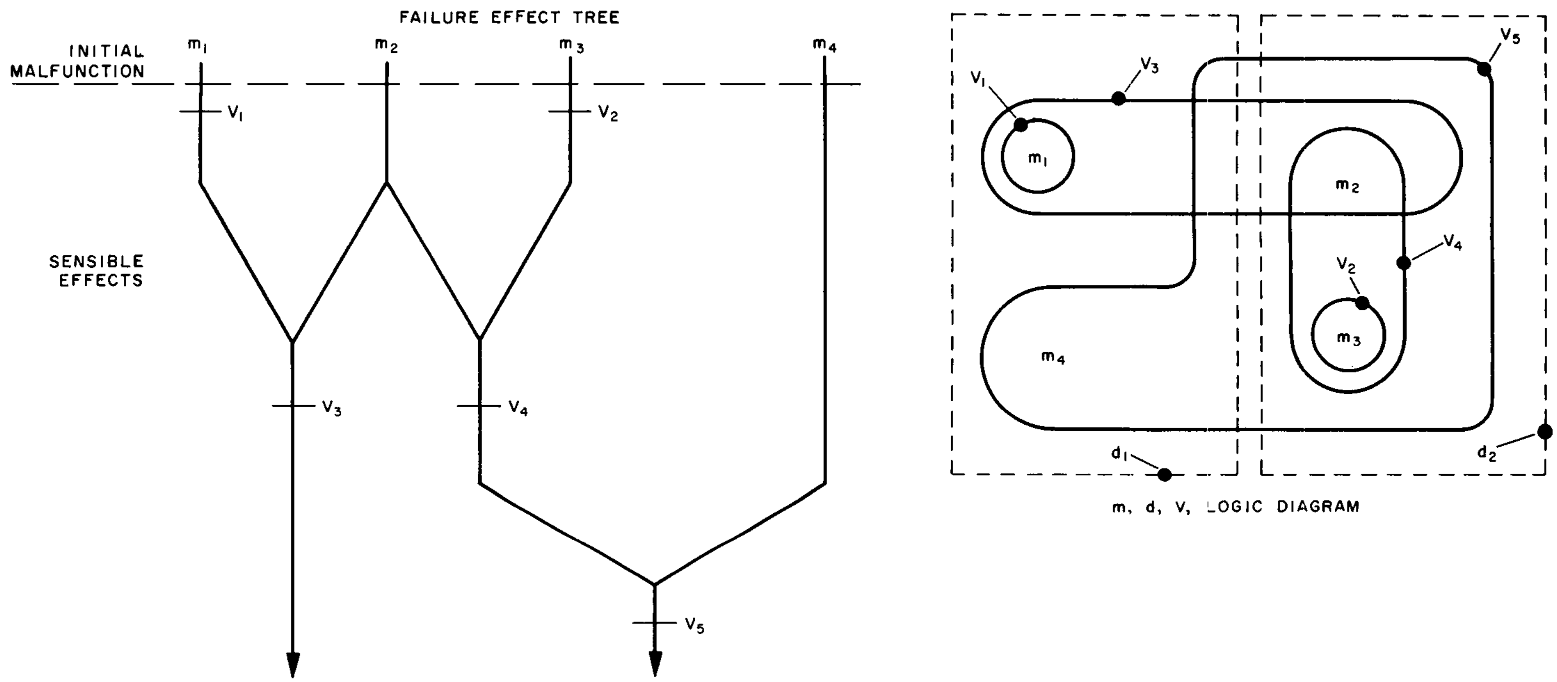


FIGURE 4-3
TYPES OF SIGNAL SPACE SEPARATIONS



LOGICAL EQUATIONS:

$$d_1 = V_1 + V_5\overline{V}_4 + V_3\overline{V}_4 + V_3\overline{V}_5 = (V_1 + V_3\overline{V}_4 + V_3\overline{V}_5) + V_5\overline{V}_4 = I_1 + I_4$$

$$\text{WHERE} \begin{cases} I_1 = V_1 + V_3\overline{V}_4 + V_3\overline{V}_5 \\ I_4 = V_5\overline{V}_4 \end{cases}$$

$$d_2 = V_2 + V_4 + V_3\overline{V}_1 = (V_2 + V_4) + (V_4 + V_3\overline{V}_1) = I_2 + I_3$$

$$\text{WHERE} \begin{cases} I_2 = V_4 + V_3\overline{V}_1 \\ I_3 = V_2 + V_4 \end{cases}$$

SYMBOLS:

m_i MALFUNCTION

$I_i(V)$ MALFUNCTION INDICATION-(SET OF V TERMS USED IN A DECISION RULE THAT INDICATES A GIVEN MALFUNCTION)

V_j SIGNAL SPACE SEPARATION-(DEFINED BY THE SET OF m_i CONTAINED IN THE V)

d_k DECISION

FIGURE 4-4
EXPANSION OF DECISION RULES

C. MALFUNCTION INDICATIONS

Malfunction indications, I_i, have been defined for use in the computational process as the group of V terms in the decision rule equation that monitors a given malfunction. By adding some redundant terms and grouping, the decision rule can be expressed in terms of the malfunction indications as shown in figure 4-4.

4-2. DESIGN PROCEDURE

The procedure that has been developed for the functional designs of a READI system is summarized in figure 4-5. The procedure is broken down into eight steps with the information flow between steps indicated by arrows. Steps 1, 2, 5, and 6 are in the engine analysis area, steps 3 and 7 are in the mission analysis area, and steps 4 and 8 are in the equipment and systems analysis area.

The first four steps (on the left-hand side of the figure) are concerned with assembling the input data for the design procedures; i. e. (1) malfunction data on the engine, (2) alternate action data on the engine, (3) data on the mission, and (4) data on the transducers available for use. Steps 5 to 8 are the analysis and synthesis procedures that progressively tie this data together to arrive at the final design.

Each of the steps is defined clearly enough so that it may be assigned as a task to a particular group, company, or individual having the specialized skills needed for its execution.

One important advantage of this type of organization is that the engine analysis expert is not required to choose which signal space separations are best for a particular system, but only to use his ingenuity to conceive and describe those that are possibilities. A digital computer will be used to actually perform the trade-off and select the best sub-set from the total set that the engine expert provides.

Effective communication between groups or steps is aided by a consistent set of symbols and definition of terms, such as signals, malfunctions, signal space separation, etc., as used in the analytical model. It has also been found useful to employ forms such as the one shown in figure 4-6, which is used by the engine analysis group to record data on possible signal space separations for use in system synthesis.

The use of these forms and other liaison requirements among the mission, vehicle, engine, and READI contractors is illustrated in figure 4-7.

4-3. CALCULATION PROCEDURE

The computation of system performance and cost has been organized for calculation on a digital computer. The calculation is performed in a number of steps, each step adding the effects of another system parameter to the approximation for the reduction in mission risk. These steps are discussed below. The equations and list of symbols are given in tables 4-1, 4-2, and 4-3.

The first step is the calculation of the risk for a perfect system which monitors all malfunctions with perfect reliability. This value will be approached asymptotically as more complete READI systems are implemented.

The second step is to compute the difference between the perfect system and a specific incomplete system that does not monitor all malfunction areas but has perfect reliability.

The next three steps compute the risk decrements due to READI failure that may result in missed alarms, false alarms, and wrong alarms.

The probabilities for the malfunction-decision pairs used in these three steps are calculated by a tracer routine. For false alarms each transducer output is perturbed to its high and low failed state and the resulting decision is determined. For missed alarms a malfunction is assumed and then the transducer outputs are perturbed. The effects of wrong alarms have been shown to be negligible and have not been included in the program.

The cost of each trial system is also tabulated by adding in the variable part of the system cost attributable to each transducer used.

4-4. OPTIMIZATION

Each system evaluated by the computer program can be plotted on a graph such as the one shown in figure 4-8.

If the performance of a given system is equal to or less than the performance of another system having less cost, the given system is obviously a poor choice.

If all "good" systems are plotted with reduced risk expressed in dollars, the optimum system can be defined as the highest performance system for which the performance increase for

FIGURE 4-5
READI DESIGN PROCEDURE

ENGINE ANALYSIS

STEP 1

Identify possible malfunctions m_i and the probability of each for each engine phase P to get p (m_i, P).

STEP 2

Identify the alternate actions, d_K, that may be taken to correct for malfunctions.

STEP 5

Perform a failure effect study on the engine and review test data to determine the result of the malfunctions on the sensible parameters of the system. Then hypothesize signal space separations, V_j, that can be used in READI to make decisions.

STEP 6

For likely combinations of m_i and d_k including d_o (no action) estimate the degree of engine degradation resulting for each of the four categories:

a. thrust loss
b. propellant loss
c. I_{sp} loss
d. explosion hazard

MISSION ANALYSIS

STEP 3

Identify and define (by velocity error, etc.) the possible states at the end of stage firing and compute the effective risk at each state using the transitional probabilities of subsequent stages and the weighted value of final mission results.

STEP 7

Compute the loss matrix by using the rocket equation, etc., to assess the engine degradation effects (step 6) and determine the stage and state. The risk for that end state (step 3) is then the desired L (m_i, d_k).

EQUIPMENT AND SYSTEM ANALYSIS

STEP 4

For each transducer used in the signal space separation:

(a) estimate the probability of a high failure and a low failure.
(b) list each signal space separation (V_j) that would change from 1 to 0 for each type failure.
(c) list each signal space separation (V_j) that would change from 0 to 1 for each type failure.
(d) estimate the incremental system cost associated with the transducer and its installation.

STEP 8

Hypothesize sets of decision rules expressed in terms of V_j's, compute reduced risk and system cost, and select the optimum system.

Stage 2
Engine
Number M17

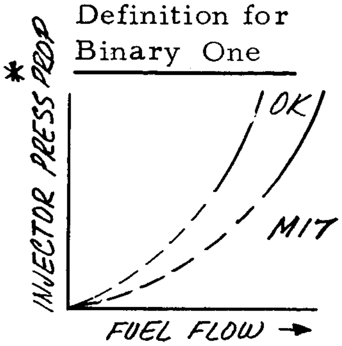
Signal Space Separation

EXCESS FUEL FLOW TO MAIN CHAMBER

Group PROPORTIONAL, COMBINATION LOGIC
Operational Modes When Used
Inputs

Code	Source Designation	t_t (ms.)
S12	FUEL FLOW (FM1)	
S25	FUEL INJECTOR PRESSURE DROP } MAIN	
S55	FUEL INJECTOR TEMPERATURE } CHAMBER	

Definition for Binary One



* CORRECTED FOR TEMP.

Processing (FOR BINARY ONE)
$S25 + \epsilon < (2 + 0.01 S55) S12 - 220$
ϵ = ACCEPTABILITY LIMIT

Failure(s)

No.	Type	Final Effect	t_F (ms.)
1	CHAMBER LEAKAGE (EXTERNAL)	EXCESS FUEL CONSUMPTING OVERBOARD LOSS	>1000
2	EXTERNAL LINE LEAKAGE	(same as 1)	
3	CHAMBER BURNOUT	EXCESS FUEL CONSUMPTION HIGH O/R, PROGRESSIVE FAILURE - ENGINE DESTRUCTION	>1000

Corrective Action(s)

No.	Action	t_c (ms.)
1	MALFUNCTION SHUTDOWN	300
2	INCREASE THRUST ON OTHER ENGINES	100

*See Detailed Discussion

READI FORM NO. 1

Stage *2*
Engine
Number *M7*

Signal Space Separation

NO PUMP SPEED

Group *BINARY COMBINATION LOGIC*
Operational Modes When Used *OPERATION (MAINSTAGE)*
Inputs

Code	Source Designation	t_t (ms.)	Definition for Binary One
S3	*FIRE VOLTAGE*		
S21	*TURBOPUMP SHUT-OFF VALVE (V6) LIMIT SW.*		*V6 OPEN*
S51	*GG FUEL INJECTOR PRESSURE*		*> 200 PSIA*
S33	*FUEL PUMP DISCHARGE PRESSURE*		*> 830 PSIA*
S6	*TURBINE SPEED*		*> 40%*
S52	*1½ SEC. DELAY FROM S3*		

Processing
(a) $(\overline{S3})(\overline{S6})(\overline{S52})$
(b) $(\overline{S3})(\overline{S21})$
(c) $(\overline{S3})(\overline{S33})(\overline{S51})$

Failure(s)

No.	Type	Final Effect	t_F (ms.)
1	*TURBOPUMP SHUT-OFF VALVE (V6) FAILED CLOSED*	*NO THRUST*	*>1000*
2	*TPSO PILOT VALVE (V10) FAILED CLOSED*	*" "*	*>1000*
3	*TURBOPUMP GEAR/BEARING FAILURE*	*" "*	*>1000*
4	*TURBOPUMP STRUCTURAL FAILURE*	*" "*	***
5	*GG RUPTURE*	*" "* *(FIRE HAZARD)*	*≈ 1000*

Corrective Action(s)

No.	Action	t_c (ms.)
1	*MALFUNCTION SHUTDOWN*	*~ 300*
2	*INCREASE THRUST ON OTHER ENGINES*	*~ 100*

*See Detailed Discussion

READI FORM NO. 1

FIGURE 4-6
SAMPLE SIGNAL SPACE SEPARATION

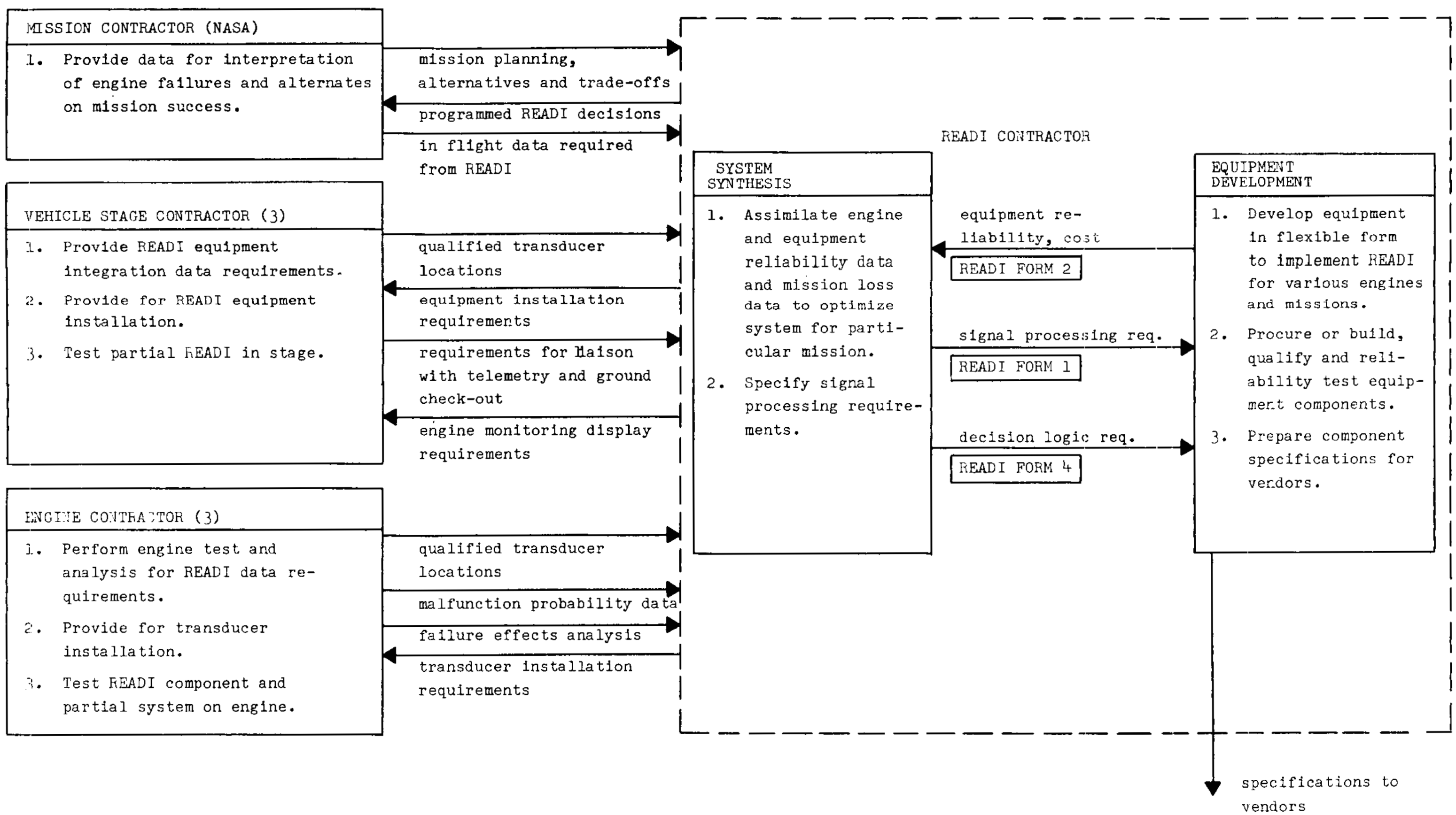


FIGURE 4-7
TASK AND COMMUNICATION DIAGRAM FOR READI DEVELOPMENT

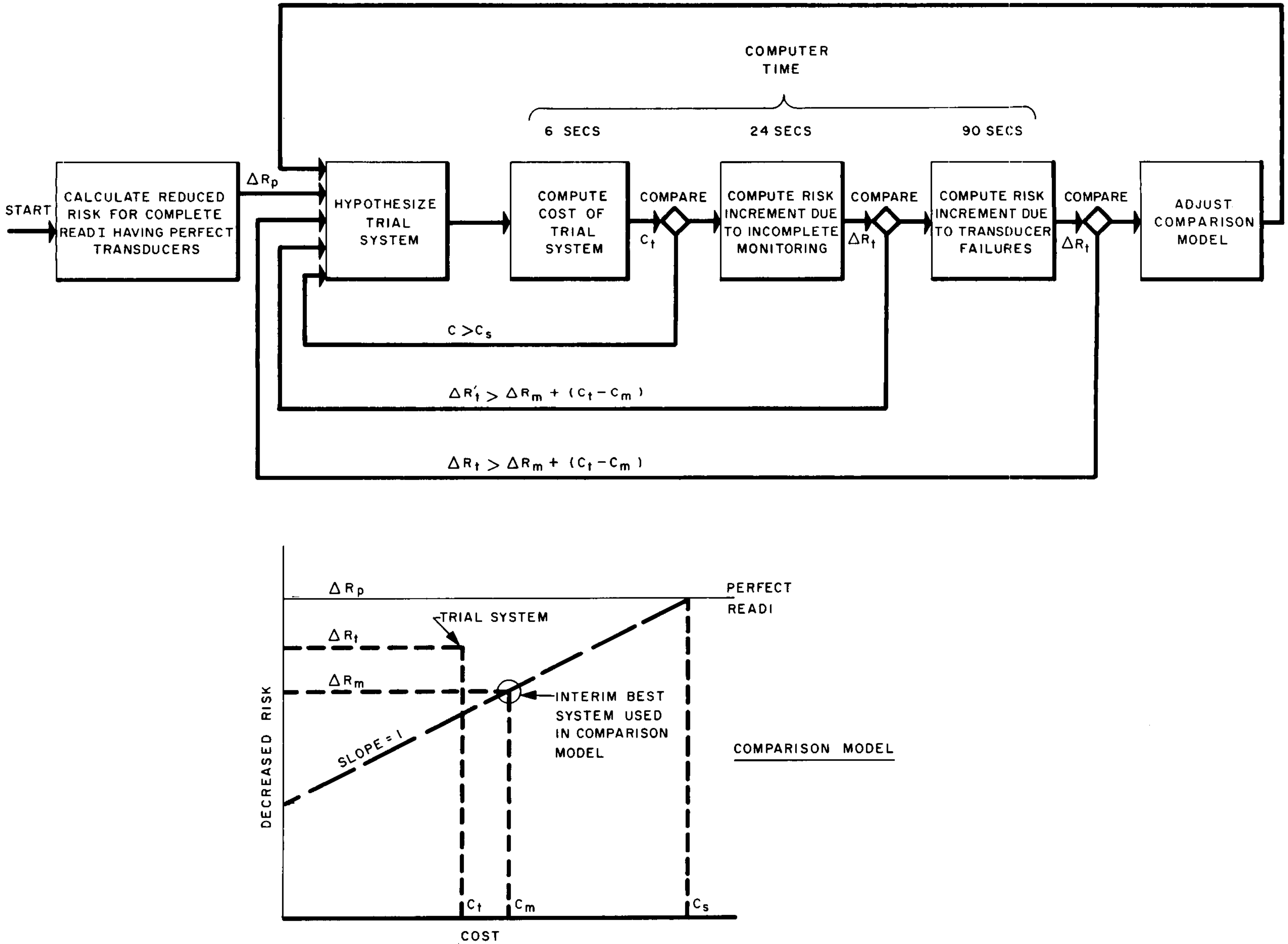


FIGURE 4-8
OPTIMIZATION PROCEDURE

the next higher performing system is less than the cost increase. This definition leads to the stored comparison model shown on figure 4-8.

The computer evaluation sequence is organized so that the successive increments decrease system performance, hence the answer can be inspected after each step in the computation to eliminate many poor systems without going through the complete computation.

TABLE 4-1

BASIS OF INCREMENTAL RISK EXPRESSION

Source	Algebraic Expression
Risk Reference (Perfect System)	$\sum_{p=1}^{5} \sum_{i=0}^{I} L_p(d_{k_i}, p; m_i) P(m_i, p)$ (1)
Risk Decrement Due to not Monitoring all Malfunction Areas (Transducer Perfect system)	$\sum_{p=1}^{5} \sum_{i=0}^{I} (1-S_{i,p}) [L_p(d_{o}, p; m_i) - L_p(d_{k_i}, p; m_i)] \cdot P(m_i, p)$ (2)
Risk Decrement Due to Missed Alarms	$\sum_{p=1}^{5} \sum_{i=0}^{I} S_{i,p} [L_p(d_{o}, p; m_i) - L_p(d_{k_i}, p; m_i)] \cdot P(d_{o,p} = 1/m_i) P(m_i, p)$ (3)
Risk Decrement Due to False Alarms	$\sum_{p=1}^{5} \sum_{k=1}^{ks} [L_p(d_{k}, p; m_o) - L_p(d_{o}, p; m_o)] \cdot P(d_{k,p} = 1/m_o) P(m_o, p)$ (4)
Risk Decrement Due to Wrong Alarms	$\sum_{p=1}^{5} \sum_{i=1}^{I} \sum_{j=1}^{ks} [L_p(d_{k_j}, p; m_i) - L_p(d_{k_i}, p; m_i)] \cdot P(d_{k_j,p} = 1/m_i) P(m_i, p)$ (5)
Incremental Risk	$\Delta R = (1) + [(2) + (3) + (4) + (5)]$

L_p loss in phase, p

d decision rule

m malfunction

$S_{i,p}$ I if m_i monitored in phase p

P probability

Subscripts

p phase index

k decision index

i malfunction index

o indicates no action or no malfunction

TABLE 4-2

FINAL FORM OF INCREMENTAL RISK EXPRESSION

Source	Algebraic Expression
Risk Reference (Perfect System)	$\sum_{p=1}^{5} \sum_{i=1}^{I} L_p(d_{k_i}, p; m_i) P(m_i, p)$ (1)
Risk Decrement Due To Not Monitoring All Malfunction Areas (Transducer Perfect System)	$\sum_{p=1}^{5} \sum_{i=1}^{I} (1-S_{i,p}) [L_p(d_o, p; m_i) - L_p(d_{k_i}, p; m_i)] \cdot P(m_i, p)$ (2)
Risk Decrement Due To Missed Alarms	$\sum_{p=1}^{5} \sum_{i=1}^{I} S_{i,p} [L_p(d_o, p; m_i) - L_p(d_{k_i}, p; m_i)] \cdot P_p(I_i = 0/m_i) P(m_i, p)$ (3)
Risk Decrement Due To False Alarms	$\sum_{p=1}^{5} \sum_{k=1}^{ks} L_p(d_k, p; m_o) P(d_{k,p} = 1/m_o) P(m_o, p)$ (4)
Risk Decrement Due To Wrong Alarms	Assumed Negligible
Incremental Risk	$\Delta R = (1) + [(2) + (3) + (4)]$

TABLE 4-3

SYMBOLS

Symbol	Definition
p	Engine phase index numbers, p = 1, ---, 5.
i	Malfunction area index number.
k	Decision rule index number.
$d_{k,p}$	Decision k in engine phase p.
$d_{o,p}$	"No action" decision in engine phase p.
$d_{k_i,p}$	The programmed decision for malfunction area i in engine phase p.
m_i	Malfunction area i.
m_o	No malfunction.
$Lp(d_{k_{i},p};m_i)$	The loss incurred when m_i occurs in engine phase p and the programmed decision is made.
$Lp(d_{o,p};m_i)$	The loss incurred when m_i occurs in engine phase p and the no action decision is made.
$P(m_{i,p})$	The probability of malfunction area i in engine phase p.
$P(d_{o,p} = 1/m_i)$	The conditional probability that in engine phase p of "no action" given m_i has occurred.
$P(d_{k,p} = 1/m_o)$	The conditional probability that in engine phase p decision k is made given no malfunction has occured.
$P(d_{k_j,p} = 1/m_i)$	The conditional probability that in engine phase p decision k_j is made given malfunction i has occured.
ΔR	Incremental risk.
I	Maximum value of i for the propulsion system under consideration.
K_s	The maximum value of K for the READI system under consideration.
I_i	The malfunction indicator for m_i.
$P_p(I_i = O/m_i)$	The probability that in engine phase p that I_i = O given that m_i occurs.
$S_{i,p}$	One if m_i is monitored in engine phase p, zero otherwise.

Section V
DESCRIPTION OF A TYPICAL READI SYSTEM

SECTION V

DESCRIPTION OF A TYPICAL READI SYSTEM

5-1. INTRODUCTION

This section describes the function and design of a typical READI system for the second stage of a launch vehicle. The description of the engine, vehicle, and model mission are as presented in Section III.

Briefly, the system employs 26 transducers on each of five engines to identify 17 different failure conditions of the engines. The analyzer initiates the best of six possible corrective decisions for each engine condition. The READI system also communicates with other subsystems within the launch vehicle as shown in figure 5-1. The interface of READI with other launch vehicle subsystems is summarized in table 5-1.

5-2. READI SYSTEM INPUTS

In addition to the signals from the 26 transducers on each engine, the READI system accepts two additional voltage inputs from the engine sequence controls and certain vehicle generated signals, such as, stage time-to-go and vehicle attitude rates. The inputs may be grouped as noted in table 5-2.

The transducer types used are selected primarily to achieve high reliability. For instance, no pressure switches, position switches, or potentiometers are used. The standard pressure sensor is a simple, two-coil, flat-diaphragm, variable-reluctance device. In a few instances where high accuracy is required, strain gauge pressure sensors are used. In several instances transducer redundancy is employed to reduce either missed or false alarm rates.

TABLE 5-1

READI INTERFACE WITH
LAUNCH VEHICLE SUBSYSTEMS

	Vehicle Subsystem	Nature of Information	Purpose
Inputs to READI	1. Guidance & Control	Time-to-go	Decision & abort inhibit Predictive malfunction Detection functions
		Vehicle attitude rates	Abort computer
	2. Separation	Engine cutoff command	Stage separation
	3. RF command	All-engine shutdown	Mission abort
	4. GSE	Computer test stimuli	Pre-flight checkout of READI electronics
	5. Propellant utilization	Lox valve position	Modify malfunction indicator references
	6. Crew	Engine shutdown; engine restart; abort commands	Redundant propulsion monitor
Outputs from READI	1. Guidance & Control	Decision outputs	Thrust change anticipation
		Propellant mass flow rates	Fuel energy management
	2. Telemetry	Raw engine data	Redundant propulsion monitoring & recording
		Transducer & computer self-check	READI status evaluation
		Malfunction indicators & decisions	READI assessment - override control
	3. GSE	Transducer self-check	Transducer status evaluation
		Computer response to GSE stimuli	Computer status evaluation
	4. Displays	Status info; predictive info	Crew monitoring of propulsion system

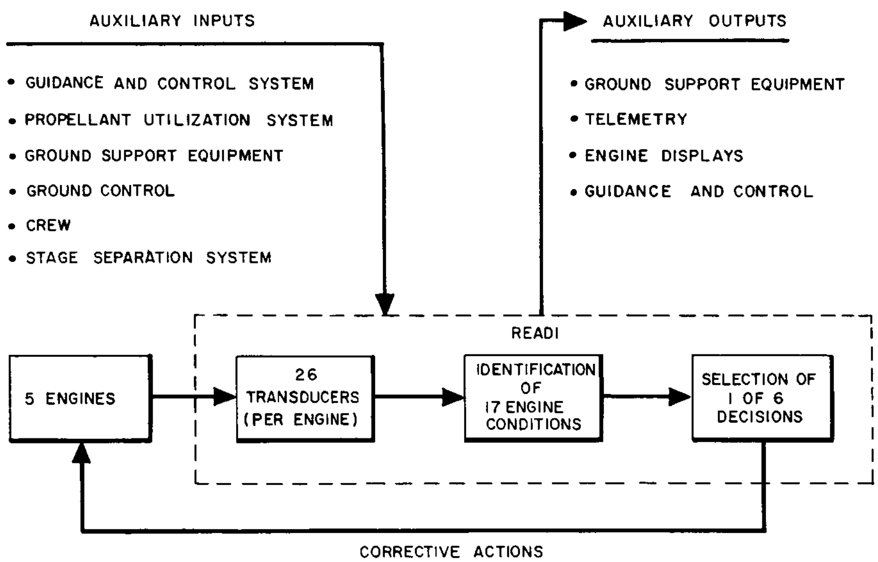


FIGURE 5-1

TYPICAL SECOND STAGE READI SYSTEM

TABLE 5-2

INPUTS TO SECOND STAGE

Number of Inputs	Type of Measurement
2	Electrical signal from engine sequence control
2	Propellant flow
10	Pressure
2	Turbine speed
2	Engine fire
4	Valve position
4	Temperature
2	Vibration

All sensors except the fire detector and the valve position indicators depend on stored references within the READI circuitry. This approach simplifies the sensors and leads to greater system flexibility.

5-3. SIGNAL PROCESSING AND IDENTIFICATION OF ENGINE CONDITION

The processing of raw input information by the READI electronics involves operations such as:

- Comparison of input to fixed limits
- Comparison of input to time dependent limits
- Arithmetic operations such as
  - scaling of signals
  - addition, subtraction, and multiplication of signals
- Comparison of processed signals.

For instance, the processing circuitry employs 31 stored references for the input signals. Some inputs, for example turbine speed, are referenced or quantized to a number of different levels for identification of different engine conditions.

In some cases, the processed signals are indicators of engine condition. However, most identifications of engine condition are accomplished by Boolean combinations of processed signals. For instance, the equation for fuel pump cavitation, which is the example failure discussed later in the section, is of the form (S52) (S6) (S33). The significance of each term will be explained in the example.

Seventeen major engine failure areas are identified and three broad failure areas are identified as a back up on the the primary indicators. The failure areas identified on the statistical model of the READI engine are noted in table 5-3 along with the estimated failure probability per mission. The engine stations and valves referred to in the table are shown in figure 5-2, the model engine fluid schematic.

5-4. READI SYSTEM OUTPUT DECISIONS

There are six pre-programmed decisions that can be selected by the decision logic. The decisions are the basic alternate action capabilities of the engines taken singly, in groups, and in sequence.

The model engine has the capability of shutting down normally and in an emergency (fast) mode, and can restore lost thrust by attempted restart and by exercising engine-out-capability. The model engine has a 20 percent thrust overrating capability, but the same mission effect could be achieved by allowing the engines to burn longer with an attendant payload penalty. The engine alternates and resulting decisions are shown below.

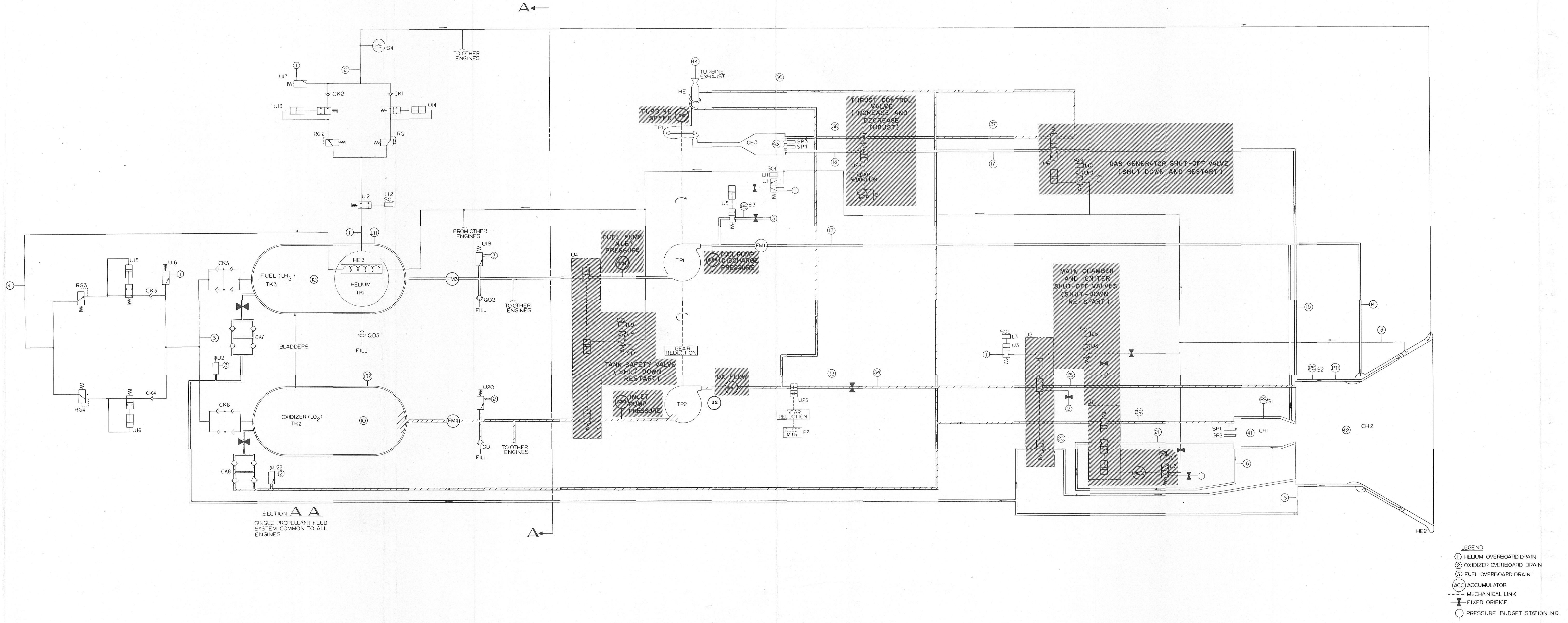
<u>Alternate Actions</u>

- shutdown
- fast shutdown
- restart
- fast restart
- increase thrust } other
- decrease thrust } engines

<u>Programmed Decisions</u>

- no action
- shutdown
- shutdown and increase thrust
- shutdown and increase thrust followed by restart and decrease thrust
- same as above preceded by fast shutdown
- fast shutdown and restart

The restart and decrease thrust actions are always premised on the engine having been returned to a normal state by the shutdown operation. The decision logic combines "gate" and "indicator" signals in



DESIGNATION	DESCRIPTION
LT2	OXIDIZER TANK LEVEL TRANSDUCER
LT1	FUEL TANK LEVEL TRANSDUCER
PT1	MAIN THRUST CHAMBER PRESSURE TRANSDUCER
SS1	TURBOPUMP SPEED SENSOR
SP3 SP4	GAS GENERATOR SPARK PLUG
SP1 & SP2	IGNITER SPARK PLUG
CH3	TURBINE GAS GENERATOR
CH2	MAIN THRUST CHAMBER
CH1	MAIN THRUST CHAMBER IGNITER
FM4	OXIDIZER FLOW METER, TOTAL
FM3	FUEL FLOW METER, TOTAL
FM2	OXIDIZER FLOW METER, ENGINE
FM1	FUEL FLOW METER, ENGINE
TR1	TURBINE
TP2	OXIDIZER PUMP
TP1	FUEL PUMP
S4	CONTROL GAS PRESSURE SWITCH
S3	FUEL PUMP PRIME PRESSURE SWITCH
S2	MAIN CHAMBER PRESSURE SWITCH
S1	IGNITER CHAMBER PRESSURE SWITCH
QD3	HELIUM TANK QUICK DISCONNECT
QD2	FUEL TANK QUICK DISCONNECT
QD1	OXIDIZER TANK QUICK DISCONNECT
CK5 – CK8	QUADRUPLE CHECK VALVE
CK1 – CK4	CHECK VALVE
HE3	HELIUM TANK HEAT EXCHANGER
HE2	HELIUM HEAT EXCHANGER
HE1	OXIDIZER HEAT EXCHANGER
TK3	FUEL TANK
TK2	OXIDIZER TANK
TK1	HELIUM TANK
RG4	SECOND STAGE HELIUM PRESSURE REGULATOR
RG3	SECOND STAGE HELIUM PRESSURE REGULATOR
RG2	FIRST STAGE HELIUM PRESSURE REGULATOR
RG1	FIRST STAGE HELIUM PRESSURE REGULATOR
B2	ELECTRIC MOTOR, OXIDIZER O/F CONTROL VALVE
B1	ELECTRIC MOTOR, TURBOPUMP CONTROL VALVE
U25	OXIDIZER O/F CONTROL VALVE, ELECT. MTR. OPERATING
U24	TURBOPUMP CONTROL VALVE, ELECT. MTR. OPERATING
U22	PRESSURIZATION RELIEF VALVE, OXIDIZER
U21	PRESSURIZATION RELIEF VALVE, FUEL
U20	OXIDIZER TANK RELIEF VALVE
U19	FUEL TANK RELIEF VALVE
U18	SECOND STAGE REGULATOR RELIEF VALVE
U17	FIRST STAGE REGULATOR RELIEF VALVE
U16	SECOND STAGE REGULATOR MALFUNCTION VALVE, PNEUMATIC OPERATING
U15	SECOND STAGE REGULATOR MALFUNCTION VALVE, PNEUMATIC OPERATING
U14	FIRST STAGE REGULATOR MALFUNCTION VALVE, PNEUMATIC OPERATING
U13	FIRST STAGE REGULATOR MALFUNCTION VALVE, PNEUMATIC OPERATING
U12	HELIUM PRESSURIZING VALVE, SOLENOID OPERATING
U11	FUEL PUMP PRIME VALVE, PILOT VALVE, SOLENOID OPERATING
U10	TURBOPUMP SHUTOFF VALVE, PILOT VALVE, SOLENOID OPERATING
U9	ENGINE SAFETY VALVE, PILOT VALVE, SOLENOID OPERATING
U8	MAIN PROP VALVE, PILOT VALVE, SOLENOID OPERATING
U7	IGNITER PROP VALVE, PILOT VALVE, SOLENOID OPERATING
U6	TURBOPUMP SHUTOFF VALVE, PNEUMATIC OPERATING
U5	FUEL PUMP PRIME VALVE, PNEUMATIC OPERATING
U4	ENGINE SAFETY VALVE, PNEUMATIC OPERATING
U3	FAST SHUTDOWN VALVE, SOLENOID OPERATING
U2	MAIN PROP VALVE, PNEUMATIC OPERATING
U1	IGNITER PROP VALVE, PNEUMATIC OPERATING

FIGURE 5-2

READI MODEL ENGINE-FLUID SCHEMATIC

TABLE 5-3

FAILURE AREAS IDENTIFIED BY TYPICAL READI SYSTEM

λ_m = per mission failure rate

Low Fuel Flow
- a. Clogged injector
- b. Fuel leakage (Stations 11-12)

$\lambda_m = 0.00078$

Low Ox Flow
- a. Clogged injector
- b. Ox leakage (Stations 31-32)

$\lambda_m = 0.00036$

Loss of Fuel to One Engine
- a. Pump cavitation

$\lambda_m = 0.00050$

Loss of Ox to One Engine
- a. Pump cavitation

$\lambda_m = 0.00020$

Engine Compartment Fire
- a. Turbine exhaust Duct failure

$\lambda_m = 0.00040$

High Gas Generator O/F
- a. Clogged injector
- b. Injector erosion
- c. External leakage
- d. HE_1 burnthrough

$\lambda_m = 0.00045$

Loss of Ox and Fuel
- a. U4 closed
- b. U9 closed

(Tank Safety Valve)

$\lambda_m = 0.00039$

Premature Igniter Flow
- a. U1 open
- b. U7 open

(Igniter Prop. Valve)

$\lambda_m = 0.00006$

Loss of Main Chamber Flow
- a. U2 closed
- b. U8 closed

(Main Prop. Valve)

$\lambda_m = 0.00024$

Premature Main Chamber Flow
- a. U2 open
- b. U8 open

(Main Prop. Valve)

$\lambda_m = 0.00010$

No Fuel Prime
- a. U11 closed
- b. U5 closed

(Prime Valve)

$\lambda_m = 0.00019$

Premature Fast Shutdown
- a. U3 open

(Fast Shutdown Valve)

$\lambda_m = 0.00012$

Vibration (Rough Combustion)

$\lambda_m = 0.00180$

High Fuel Flow
- a. Chamber burnout
- b. Injector erosion
- c. External leakage (Chamber area)

$\lambda_m = 0.00060$

High Ox Flow
- a. Injector erosion
- b. External leakage (Chamber area)

$\lambda_m = 0.00045$

No Pump Speed
- a. U6 or U10 closed
- b. GG structural failure
- c. Gear or bearing failure
- d. Pump structural failure
- e. Turbine or nozzle erosion

$\lambda_m = 0.00079$

Premature Gas Generator Flow
- a. U6 open
- b. U10 open

(Turbopump Shutoff Valve)

$\lambda_m = 0.00019$

such a way that the READI decision changes with engine phase for a given engine condition. The processing from transducer to decision is clarified by the following examples.

A. EXAMPLE 1 - FUEL PUMP CAVITATION

1. Nature of the Failure

Cavitation generally results from low pump inlet pressure or high inlet temperature or a combination of conditions. There is a hazard of explosion of the engine because the propellants enter the chamber in an uncontrolled manner, and the spark igniters serve as the ignition source. The model engine has the following probabilities, per mission, of fuel pump cavitation by engine phase:

prestart	0.00000
start	0.00032
operate	0.00018
shutdown	0.00000

2. Corrective Action

The first corrective action step is to shutdown, to stop propellants from entering the chamber. The thrust of the other four engines is then increased by 20 percent so that 96 percent of normal stage thrust is regained. A normal restart, including the priming or prestart cycle, is then attempted. If normal operation is reached, the thrust of the other engines is reduced to normal. This sequence of actions is given the designation D_6.

The intermediate increase in thrust is programmed because the likelihood of cavitation at restart is fairly high, and in any event the priming operation can take up to 20 seconds. A second restart attempt is not programmed in case the pump cavitates the second time.

3. Identifying the Engine Condition

There is no marked advantage in sensing the conditions leading to fuel pump cavitation because: the pump inlet pressure-temperature starting map is not well defined as a rule, and there is nothing which can be done directly to change the inlet conditions.

Signals were selected, therefore, which indicate the occurrence of cavitation (figure 5-3).

Signals

Symbol	Designation	Processing
S33	fuel pump discharge pressure	< 550 psia
S32	ox pump discharge pressure	> 740 psia

Logic

$$D_6 = (S32)\ (S33)$$

The above equation is read, "ox pump discharge pressure greater than 740 psia, but pump discharge pressure below 550 psia." Note that the first two terms serve as "gates" since they are binary one normally, while S33 "indicates" the condition. Whenever the above equation occurs, i. e., all three terms equal one, the programmed decision is invoked.

4. Back-Up

The model READI system also identifies other engine conditions which result from pump cavitation. These effects are farther down the failure effects tree from the (S32) (S33) combination discussed before. They are turbine overspeed and loss of chamber pressure. Pump cavitation is almost always followed by a pump overspeed transient, and always by loss of chamber pressure. However, since a large number of engine failures lead to these effects, it would be dangerous to program a restart. Therefore, the decision for overspeed and loss of chamber pressure is to shutdown and increase thrust on the other engines. Since this decision is non-optimum for pump cavitation, the indicating threshold of the back-up signals is set so that the (S32) (S33) equation will obtain before the overspeed or chamber pressure indicators. The latter, therefore, serve as a back-up on the cavitation failure and a number of other engine failures as well.

B. EXAMPLE 2 - LOW OXIDIZER FLOW TO MAIN THRUST CHAMBER

1. Nature of the Failure

Low oxidizer flow to the main chamber is a failure area which includes the effects of several initial failures. The dominant effects are caused by clogged oxidizer injectors and external oxidizer

leakage. These effects lead to loss of thrust and possible loss of unburned oxidizer overboard. The probability of failure figures used in the evaluation were selected to represent fairly serious engine deterioration with an attendant explosion hazard.[1] The following failure probabilities were used for "low oxidizer flow".

prestart	0.00000
start	0.00003
operate	0.00028
shutdown	0.00000

2. Corrective Action

Because of the explosion hazard and overboard loss of oxidizer, the first step is to shutdown the engine. As in the previous example, the thrust of other engines is increased by 20 percent so that 96 percent of stage thrust is achieved. No restart is attempted. These actions are designated D_4.

3. Identifying the Engine Condition

Two separate identifications are made to define the existence of this failure. Either of these will result in initiating corrective action. This malfunction area is an example of a case where there is a fairly clear separation of failures (i. e. clogged injectors and leaks) but an overlapping in the engine condition identification. The table below shows the signal processing and logic and figure 5-4 shows the tie-in of the logic with the engine. Figure 5-5 summarizes the signals, processing, and actions for low oxidizer flow.

- - - - - - -

[1] For "proportional" failures of this kind, a relatively large failure probability figure usually implies that a large number of minor magnitude failures are included in the sample. Conversely, a small failure probability figure may imply that only gross failures are included.

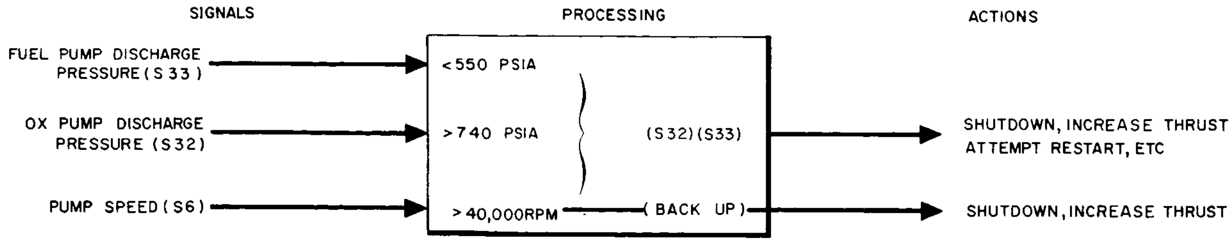


FIGURE 5-3
SUMMARY OF PROCESSING AND LOGIC FOR FUEL PUMP CAVITATION

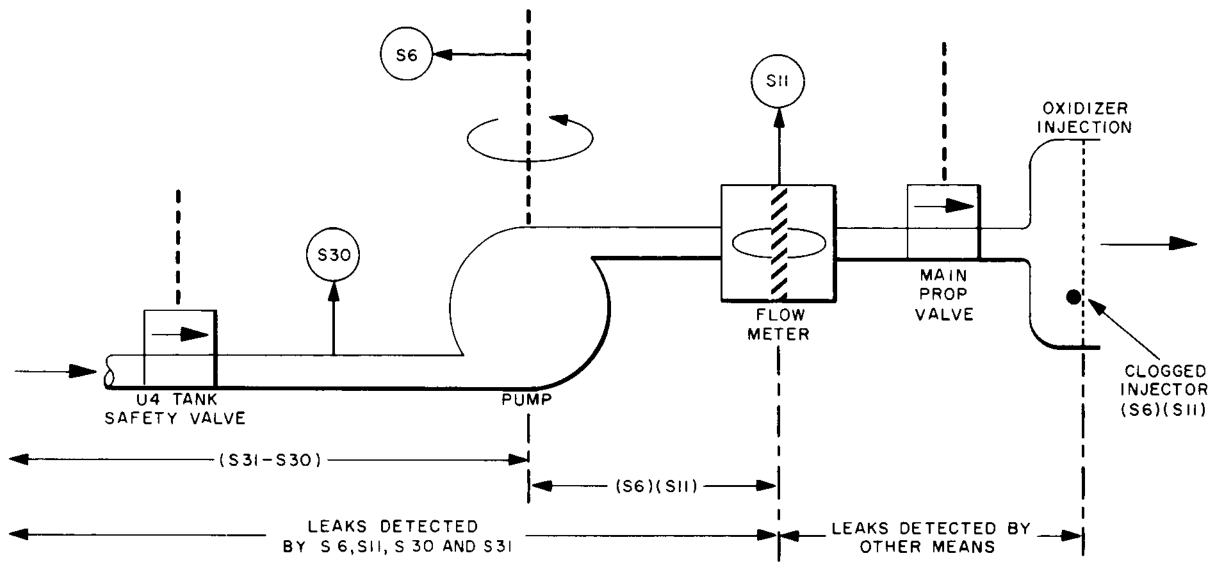


FIGURE 5-4
IDENTIFICATION OF LOW OXIDIZER FLOW

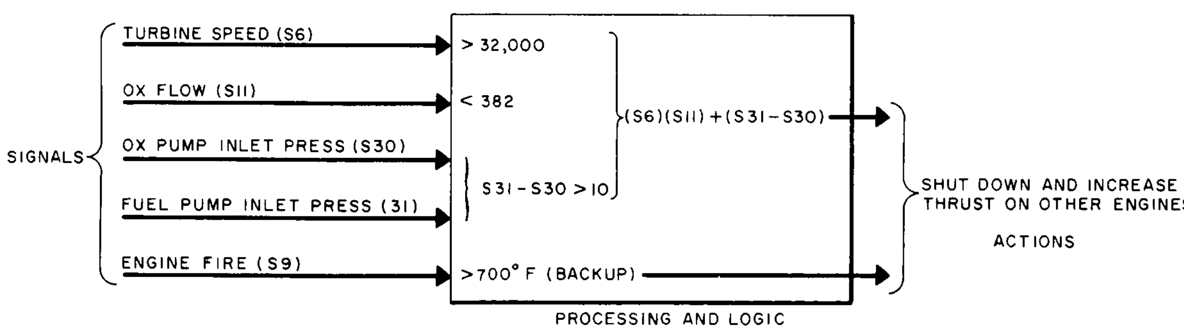


FIGURE 5-5
SUMMARY OF SIGNALS PROCESSING AND ACTIONS FOR LOW OX FLOW

Signals

Symbol	Designation	Processing
S6	turbine speed	> 32,000 rpm
S11	ox flow	< 382 lb/sec
S30	ox pump inlet pressure	(S31-S30) > 10 psia
S31	fuel pump inlet pressure	

Logic

$$D_4 = (S6)\ (S11) + (S31-S30)$$

The (S6) (S11) term indicates clogged injectors and leaks between the pump outlet and flowmeter, including pump leaks, while the (S31-S30) term indicates leaks upstream of the pump. Leaks between the flowmeter and oxidizer injector fall into a different category and are identified by other means.

4. Back-Up

The low oxidizer flow failure area is backed-up, in part, by the engine fire detector signal, since fire will result, in some instances, from oxidizer leaks. The turbine overspeed and chamber pressure back-up signals, mentioned in the pump cavitation example, will not indicate. The decision for fire is in this case the same as for the primary identification; i. e., shut down and increase thrust on remaining engines.

5-5. ELECTRONIC SYSTEM

The computations and logical operations described for the typical system will be performed by a system such as the one shown in figure 5-6. It is referred to as a hybrid system since the computational and logical operations are performed by both parallel wired digital circuitry and a series type digital computer. The parallel wired circuitry is used for data channels involving simple computations, thereby unloading the digital computer and multiplexer which handle the more complicated processing channels. The digital computer can then be of the simple series type with relatively low bit rates and very reliable wired magnetic core types of program and data storage.

The requirements for flexibility and reliability were perhaps the most important considerations in arriving at this design. Flexibility or versatility is required in order to allow for parallel development and growth of the engines and the READI system. Programmed READI operation must be readily changed as more information becomes available about the engine from test data and flight experience. Stored functions and limits must be changeable, and it should be possible to add or delete transducers and processing channels as required. It should also be possible to vary the programming of READI as a function of the mission for a given vehicle. An unmanned mission, for instance, might be programmed quite differently from a manned mission for some malfunction types.

The critical problem areas in terms of reliability have been identified as the transducers with their associated cabling, and the time shared components of serial digital computer channels including the analog-to-digital converter. The reliability of the parallel wired computation circuitry does not appear to be a problem, if integrated microcircuitry is used in accordance with the best design techniques.

A number of techniques have been devised for achieving adequate system reliability using current state-of-the-art transducers and electronic components. These techniques utilize transducer checks, circuitry function tests, equipment and information redundancy, and reasonableness checks on input data. The problem has been to decide where and to what degree these techniques should be implemented. This question can be answered by determining the loss in system value due to false or missed alarms for a given malfunction channel as a function of failure rate. Then decisions can be made as to how much increase in system cost for redundancy and other reliability improvement techniques is justified by the improved performance obtained. Figure 5-7 illustrates a typical trade-off chart used for this purpose. The higher penalty due to false alarms would suggest that the system be designed to reduce false alarms even at the expense of some increase in missed alarms.

An understanding of the application of these reliability techniques and the operation of the electronics can perhaps best be obtained by consideration of a particular example. For this purpose the two malfunction channels described in the previous sections will be adopted. The pump cavitation, m_4, channel utilizes the parallel wired logic, while the low oxidizes flow malfunction, m_3, utilizes the more complex digital computer processing.

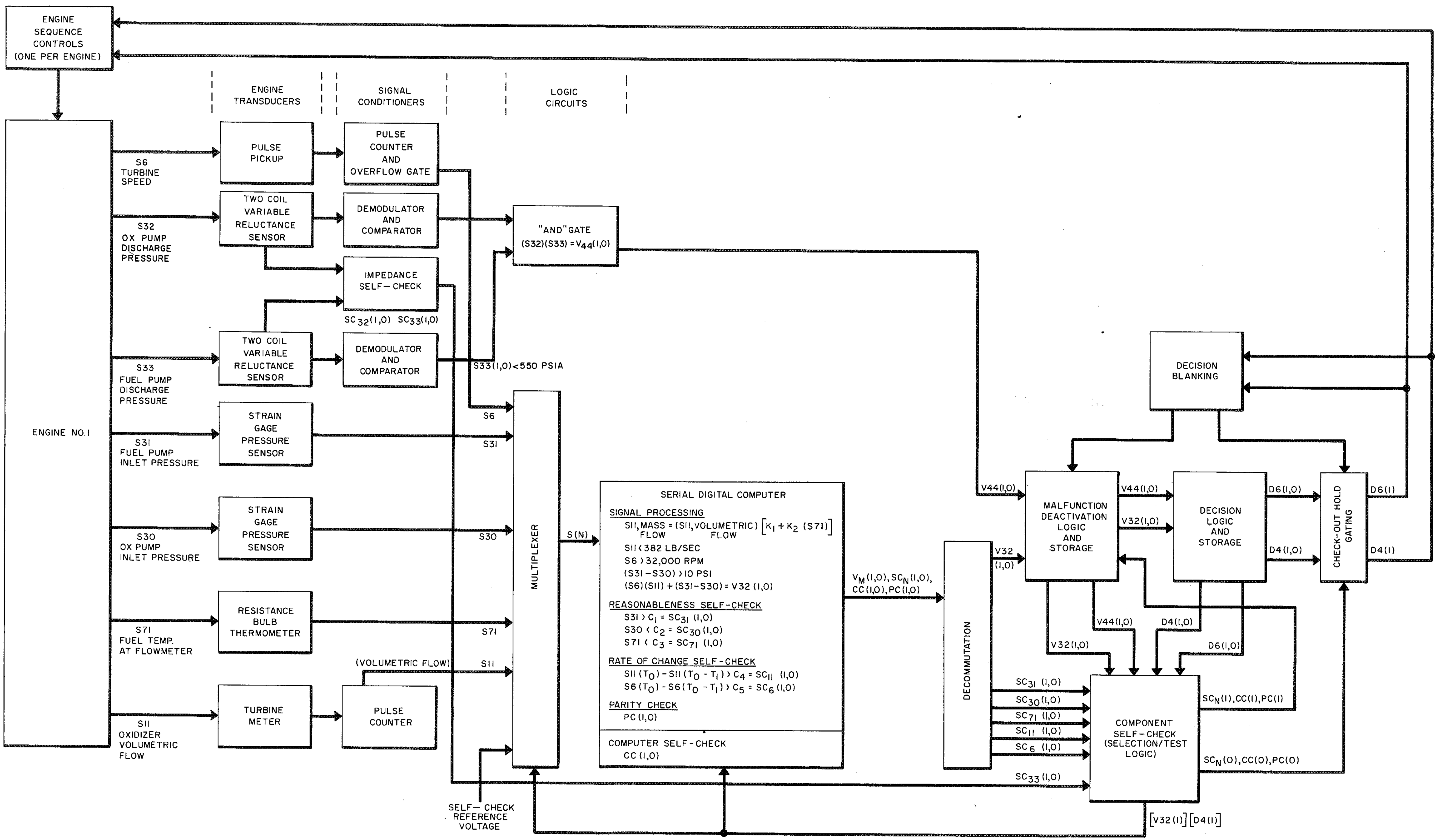


FIGURE 5-6
TYPICAL SIGNAL PROCESSING

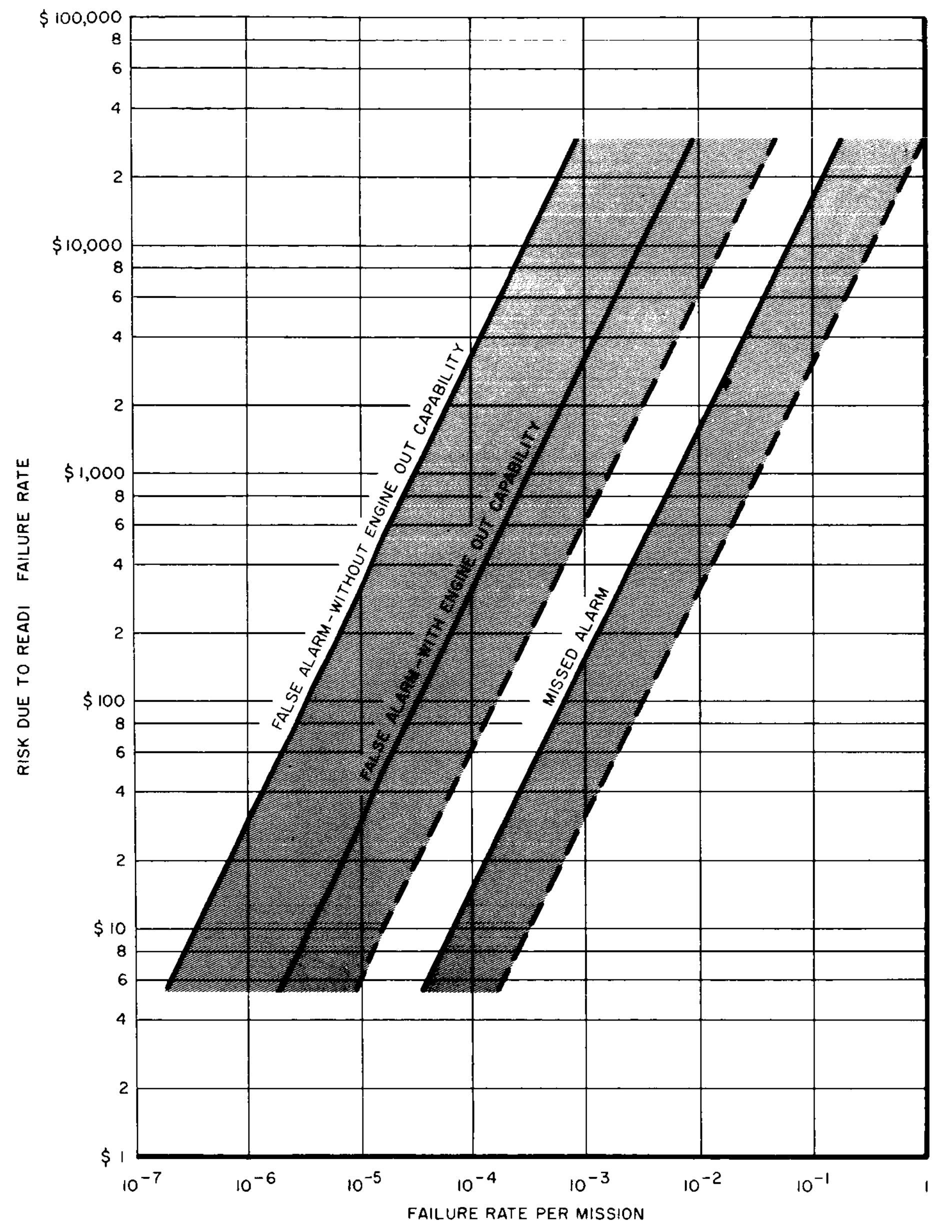


FIGURE 5-7

SENSITIVITY OF RISK TO READI FAILURE RATE FOR TYPICAL ENGINE CONDITION IDENTIFICATION CHANNEL

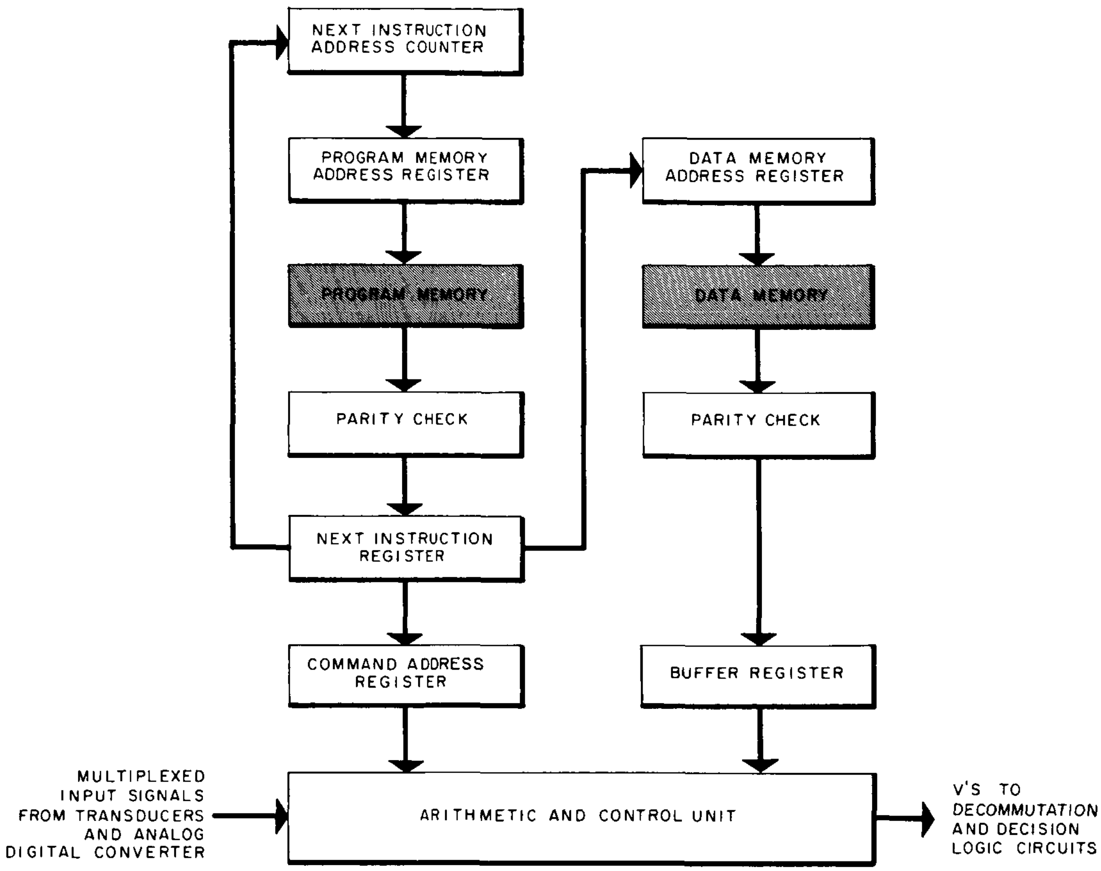


FIGURE 5-8

DIGITAL COMPUTATION
BLOCK DIAGRAM

A. PUMP CAVITATION

To detect pump oxidizer cavitation, m_4, two engine transducer signals are used, S32, oxidizer pump discharge pressure and S33 fuel pump discharge pressure. The pressure signals, S32 and S33, are determined by sensing the output voltage amplitude of the two coil variable reluctance sensors and comparing them to reference voltages equivalent to 550 psia and 740 psia. Since the output of the sensor is an a-c voltage, the signal is demodulated first before comparison in the d-c comparator. The output state of the comparator is the required indicator, S33 (1, 0), defined in malfunction m_4. A 1 state of the comparator output indicates that the pressure is less than 550 psia, while a 0 state indicates greater than 550 psia.

To improve the reliability of the gate and indicator, self-check is performed on the transducers which are the most unreliable elements in the malfunction detection channels. The pulse pickup transducer is self-checked by the measurement of the rate of change of the output. This will be explained later in this section. The variable reluctance sensor is self-checked by another method through the impedance measurement of the transducer's electrical element. Since the electrical element is part of a bridge circuit, a high or low current through the bridge will indicate a short circuit or open circuit of the transducer elements or associated cabling. By sensing this abnormal current flow, a transducer failure resulting in false alarm, SC_{32} (1), or SC_{33} is indicated at the output of the self-check circuit. The use of this false alarm signal will be described later in the discussion of the component self-check logic.

When these signals are combined in an AND gate logic circuit, the malfunction indicator V44 (1, 0) is generated in accordance with the following Boolean expression:

$$V44\,(1) = [S32\,(1)] \quad [S33\,(1)]$$

where (1) is the state of the gates and the indicator.

The indication of V44 (1) is next conducted to the malfunction deactivation logic and storage which results in the generation of a potential decision when processed by the decision logic. The malfunction (m_4) requires only one malfunction indicator V44 (1, 0); however, in some cases more than one malfunction indicator may be used to arrive at the correct remedial action. The potential decision is now blocked from the engine controls by the checkout hold gating.

The malfunction detection deactivation logic and the checkout hold gating inhibit the malfunction indicators and potential decisions if there is some reason why the correctness of the signal or decision would be suspect, such as:

- another malfunction of higher priority has occurred
- transients or off-design operation has been induced by a previous remedial action decision
- a READI transducer or equipment failure.

Providing the above conditions are met, decision D_6, which shuts down the engine and increases the thrust on the other engines, is conducted to the engine controls. A restart is attempted after a suitable time delay, and if the restart is successful, the thrust on the other engines is reduced to the normal level. If the restart is unsuccessful, the engine is shutdown for the balance of the mission. The applicable checkout data is determined by the component self-check logic circuitry which responds to different V and D inputs. In this case two transducer checks are made, an impedance check of the fuel and oxidizer pump discharge pressure transducers, SC_{32} (1, 0) and SC_{33} (1, 0).

If all these inputs checkout correctly, the decision is implemented. The detailed engine sequencing is performed by the engine control system. The READI system transmits information to this control by voltage on wires 1 and 3.

B. LOW OXIDIZER FLOW TO MAIN THRUST CHAMBER

To detect low oxidizer flow m_3, five engine transducer signals are used:

S30,ox pump inlet pressure

S31, fuel pump inlet pressure

S71, ox temperature at flow meter

S11, oxidizer volumetric flow

S6, turbine speed.

Since the computations for this malfunction area are performed by the serial digital computer, the outputs of the five transducers must be converted to a compatible form and then multiplexed.

Two of the transducer outputs are in the form of frequencies and are processed by a pulse counter. The pulse counter is interrogated periodically by a command signal and read out in serial binary form. The resistance thermometer and the two strain gage type pressure transducers are multiplexed into the analog-digital converter for conversion to binary form.

Organization of the digital computation is shown in figure 5-8. The signal processing for the low oxidizer flow malfunction consists of arithmetic operations and comparisons of the outputs of the five transducers.

The arithmetic and control unit performs these actual operations according to a wired magnetic core (rope) program memory. This program can only be changed by rewiring of the cores and is not subject to destruction by computer malfunction or power failure. The constants used in the equation are also stored in a magnetic core (rope) memory, while the temporary storage of data required for the arithmetic operations is stored in an alterable memory, using bi-aperture cores to allow nondestructive readout.

Each program or data word stored in the memory has a parity check bit that indicates whether the number of 1's in the word is even or odd. As each word is read out, the parity check is used to detect the occurrence of a random error in a single bit.

In addition to the actual signal processing, the programming also includes instructions for the reasonableness check on data, the rate of change self-check, and the computer self-check. The reasonableness self-check method uses the upper and lower operating limits of the transducer or parameter under measurement to determine if the actual transducer output is reasonable when compared to the stored limit values. The rate of change self-check method senses the differences between the predicted rate of change of the measured parameter and a catostrophic transducer failure. The computer self-check is implemented by introducing a known input through the multiplexer and analog-to-digital converter to be processed by the serial digital computer and compared to the correct stored value. If the computed value differs from the stored memory value, the digital computer transmits a signal to the component self-check logic indicating improper operation.

The processed output data comes out of the computer in series form and is decommutated into the output circuitry which was described in connection with the parallel wired example. Any READI equipment malfunctions automatically lock-out decisions that might be affected by the malfunctioning parts which results in the equipment having a very high reliability.

Section VI

CONCLUSIONS AND RECOMMENDATIONS

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CONCLUSIONS AND RECOMMENDATIONS

A philosophical approach plus a step-by-step procedure have been developed for the design and evaluation of a Rocket Engine Analyzer and Decision Instrumentation System. This approach is believed to have a number of advantages over purely intuitive designs in that it clearly identifies the input data and assumptions used, and establishes relationships among parameters for use in making the best trade-off decisions.

Development of a system for an actual space mission will be facilitated by this procedure since it will be possible to make concise task assignments to the development team and to specify data and other requirements to the various engine, stage, and vehicle contractors. The automated data processing and system evaluation program will allow for continuous assessment of system changes that may be required due to engine changes and data improvement.

Although trial systems can be evaluated very rapidly using this program, a true optimization subroutine has not been developed. It is recommended that further effort be applied to determine the most practical synthesis subroutine.

The proposed equipment design has the capability of accommodating growth changes and changes in programming required for different missions. The equipment employs special test and reliability provisions that allow it to meet the stringent system reliability requirements. It is recommended that a partial system be implemented to test the ability of the equipment to tolerate various transducer and component failures without false alarm.

An investigation of the economic feasibility of applying the READI concept to a typical mission and vehicle engine combination has demonstrated a very high potential pay-off. However, the conclusions have been shown to be sensitive to certain assumptions such as the alternate actions available for the engines. It is recommended that the feasibility of application to particular space vehicles and missions be investigated now, and that the feasibility of adding more control flexibility to present and future space engines be considered.

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